VOLTAGE REGULATION OF A SYNCHRONOUS GENERATOR USING MAGNETIC AMPLIFIERS

THOMAS E. AUGER

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THOMAS E. AUGER

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OF A SYNCHRONOUS GENERATOR

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by

THOMAS EARNEST AUGER
Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
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1955

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IN

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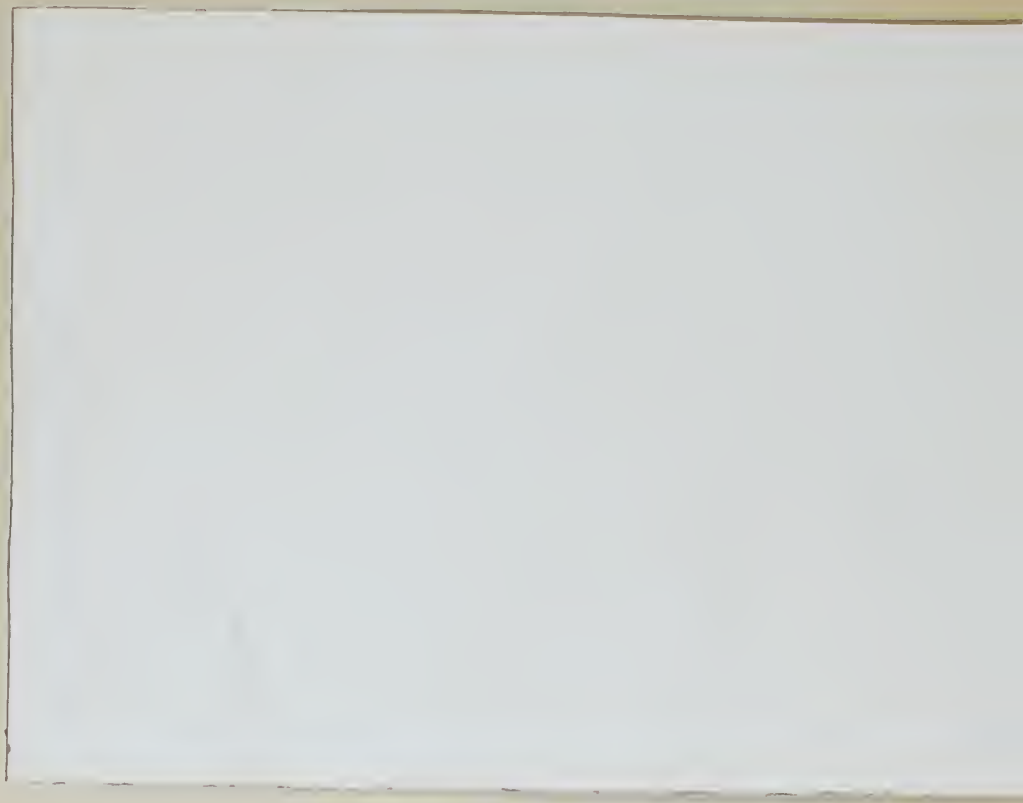

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PREFACE

This thesis subject was undertaken in an effort to become conversant with the basic characteristics of a voltage regulator and to determine the properties which make it function effectively in conjunction with a synchronous generator.

A four hundred forty volt, sixty cycle, fifteen horsepower squirrel cage induction motor, coupled by a ten horsepower magnetic particle clutch to a one hundred twenty volt, three phase, four hundred cycle synchronous generator was used in conducting this research.

It is desired to acknowledge specifically the untiring and patient guidance of Doctor George J. Thaler, of the U. S. Naval Postgraduate School, in conducting the thesis. Further, I thank collectively the members of the Electrical Engineering Department of the U. S. Naval Postgraduate School for their kind counsel and assistance in specific problems encountered.

TABLE OF CONTENTS

		Page
CERTIFICATE OF APPROVAL		i
PREFACE		ii
TABLE OF CONTENTS		iii
LIST OF ILLUSTRATIONS		v
CHAPTER I	Synopsis of Thesis Research (A) Statement of the Problem (B) Statement of the Conclusions	1
CHAPTER II	The Problem of Voltage Regulation in Electrical Machinery (A) The Bureau of Ships Voltage Regulator Problems and Long Range Objectives (B) The Simplification of the Problem in Order to Conduct This Research	3
CHAPTER III	The Method of Attacking the Problem (A) Use of Feedback Control Theory in Developing a Frequency Response Analysis (B) Determination of Performance Characteristics using Steady State and Transient Analysis Techniques (C) Use of Photographic Analysis of Wave Shapes at Main Junctions in the Voltage Regulator System	6
CHAPTER IV	Construction of Test Equipment and Instrumentation	9
CHAPTER V	The Various Tests Conducted	27
CHAPTER VI	Analysis of data	30
CHAPTER VII	Conclusions and Discussion of Results	119
CHAPTER VIII	Recommendations for Further Study	125
BIBLIOGRAPHY		127
APPENDIX I	Instruments Used In Recording Data	132
APPENDIX II	Derivation of Transfer Functions for the Various Components in the Voltage Regulator System	136

APPENDIX III	Derivation of General Solution for Determining the Roots of a Cubic Equation	149
APPENDIX IV	General Characteristics of the Motor - Clutch, and Generator Units and the Operation of the System	155
APPENDIX V	Complete Data on Load Test for Overall System	166

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Motor - Generator and Voltage Regulator System	8
2.	Voltage Regulator Panel Bus Connections	10
3.	Speed Regulator, Induction Motor, and Utility Buses	11
4.	Physical Bussing Connections for Voltage Regulator - Internal View	12
5.	Physical Bussing Connections for Voltage Regulator - External View	13
6.	Starting and Steady State Switches to Permit Reading Currents in Induction Motor	15
7.	Instrumentation of Voltage Regulator	15-A
8.	Generator Output Load and Metering Connections	19-A
9.	Instrumentation to Secure Tripler Reactor Transients	20
10.	Equipment utilized to Determine Transient and Steady State Photographic Data	21
11.	Experimental Equipment to Step Function the Tripler Reactor	22
12.	Brush Recorder Set Up for Simultaneously Recording Transients at Key Positions Throughout System	24
13.	Brush Recorder Set Up for Simultaneously Recording Transients at Key Positions Throughout System	25
14.	Circuit Diagram for Five Kilowatt Voltage Regulator	32
15.	Motor Speed in R P M versus Generator Speed in R P M	45
16.	Voltage Regulator	46
17.	Voltage Regulator Instrumentation	47
18.	System Diagram for Five Kilowatt Motor Clutch Generator Set	48
19.	Schematic Diagram of Voltage Regulator and Synchronous Alternator	49

LIST OF ILLUSTRATIONS (CONT'D)

Figure	Title	Page
20.	Schematic and Block Diagram for Voltage Regulator System	50
20-A	Block Diagram for Voltage Regulator System	34
21.	Generator Terminal Voltage Versus Generator Load Current for Various Values of Separately Excited Generator Field Voltage	61
22.	Magnetization Curve	62
23.	Generator Terminal Voltage Versus Load Current for (1) Automatic Voltage Regulation (2) Manual Voltage Regulation (3) No Regulation	63
24.	Detector Primary Voltage Versus Secondary Voltage of Transformer T1-27C61-2	64
25.	Tripler Reactor 38B55-2L1 Input Voltage Versus Output Voltage and Current	65
26.	Bridge Rectifier 1-44B30-2 Output Voltage and Current Characteristics versus Input Voltage	66
27.	Bridge Rectifier 1-44B30-2 Output Voltage and Current Characteristics versus Input Current	67
28.	Bias Rectifier 2-44C79-2 Output Voltage and Current Characteristics versus Input Voltage	68
29.	Generator Load Current versus (1) Preamplifier Control Current (2) Preamplifier Main Power Current (3) Preamplifier Output Current (4) Preamplifier Bias Current	69
30.	Current Transformer 27C68-2 Load Current versus Output Voltage and Current	70
31.	Main Power Rectifier 44C20-2 Final Stage Input Voltage versus Output Current and Voltage	71
32.	Main Power Rectifier 44C20-2 Final Stage Amplifier Input Current versus Output Current and Voltage	72

LIST OF ILLUSTRATIONS (CONT'D)

Figure	Title	Page
33.	Main Power Final Amplifier Stage Current versus Generator Field Current and Voltage	73
34.	Main Power Final Amplifier Stage Voltage versus Generator Field Current and Voltage	74
35.	Final Stage Amplifier Control Voltage versus Generator Field Current and Voltage	75
36.	Final Stage Amplifier Control Current versus Generator Field Current and Voltage	76
37.	Generator Line Current versus Generator Field Current and Generator Field Voltage	77
38.	Generator Load Current versus (1) Preamplifier Stage Control Current (2) Final Stage Control Current (3) Final Stage Main Power Current (4) Final Stage Output Current (5) Final Stage Bias Current	78
39.	Generator Load Current versus (1) Generator Terminal Voltage (2) Generator Field Voltage (3) Control Voltage Final Amplifier Stage (4) Control Voltage Preamplifier Stage (5) Bias Voltage	79
40.	Magnetic Particle Clutch Transient	87
41.	Bias Control Circuit Transients from No Load to Various Loadings	88
42.	Bias Control Circuit Transients for Various Loadings to No Load	89
43.	Preamplifier Control Circuit Transients from No Load to Various Loadings	90
44.	Preamplifier Control Circuit Transients for Various Loadings to No Load	91
45.	Final Stage Amplifier Control Circuit Transients from No Load to Various Loadings	92

LIST OF ILLUSTRATIONS (CONT'D)

Figure	Title	Page
46.	Final Stage Amplifier Control Circuit Transients for Various Loadings to No Load	93
47.	Final Stage Amplifier Main Power Transients from No Load to Various Loading	94
48.	Final Stage Amplifier Main Power Transients for Various Loadings to No Load	95
49.	Generator Field Transients for No Load to Various Loadings	96
50.	Generator Field Transients for Various Loadings to No Load	97
51.	Generator Output Voltage and Current Wave Shapes	104
52.	Detector Transformer T1-27C61-2 Input and Output Current and Voltage Wave Shapes	105
53.	Tripler Reactor L1-38B55-2 and Bridge Rectifier 1-44B30-2 Output Voltage and Current Wave Shapes	106
54.	Main Power Preamplifier Rectifier 2-44C190-2 Input and Output Current and Voltage Wave Shapes	107
55.	Bias Rectifier 2-44C79-2 Input and Output Current and Voltage Wave Shapes	108
56.	Final Stage Main Power Rectifier 44C20-2 Input and Output Current and Voltage Wave Shapes	109
57.	Preamplifier 35C63-2 Output Voltage and Current Wave Shapes and Bias Current Wave Shape	110
58.	Generator Field Voltage and Current Wave Shapes	111
59.	Magnetic Particle Clutch Voltage and Current Wave Shape, Induction Motor Current Wave Shape, and Tachometer Voltage Wave Shape	112
60.	Tripler Reactor L1-38B55-2 Expanded Voltage Transient Wave Shape	113
61.	Tripler Reactor L1-38B55-2 Voltage Transient and Steady State Wave Shapes	114

LIST OF ILLUSTRATIONS (CONT'D)

Figure	Title	Page
62.	Tripler Reactor L1-38B55-2 Expanded Voltage Transient Wave Shapes	115
63.	Preamplifier Stage Bias Current Wave Shape, Input Current and Voltage Wave Shapes to Main Power Rectifier	116
64.	Generator Field Current and Voltage Wave Shapes and Output Current Main Power Rectifier 44C-20-2	117
65.	Preamplifier 35C63-2 Main Power Input Voltage and Preamplifier Output Voltage Wave Shape	118
66.	Induction Motor - Magnetic Particle Clutch - Generator Field - Alternator Speed - and Generator Loading Characteristics Sheet One	166-A
67.	Sheet Two	167
68.	Sheet Three	168
69.	Sheet Four	169
70.	Preamplifier Stage 35C63-2 and Bias Loading Characteristics Sheet Five	170
71.	Sheet Six	171
72.	Sheet Seven	172
73.	Final Amplifier Stage 35D96-2 and Miscellaneous Loading Characteristics Sheet Eight	173
74.	Sheet Nine	174
75.	Sheet Ten	175

CHAPTER I

SYNOPSIS OF THESIS RESEARCH

The successful voltage regulation of a generator has been the pursuit of many investigators. It has been accomplished in many instances on a trial and error basis. It is felt that there are specific and measurable characteristics of the generator, which, if accurately known, would permit the design and construction of a voltage regulator before the generators were manufactured.

This investigation was able to gain an insight into some of the characteristics which make a voltage regulator function effectively. The conclusions from this investigation are:

1. The synchronous alternator characteristics which must be accurately known are:
    a. The magnetization curve at synchronous speed from zero field current to twice no load field current.
    b. The voltage regulation curves of the synchronous generator from 70% to 125% of rated terminal voltage.
    c. The design specifications for the synchronous alternator.
2. The components which are utilized in the construction of the voltage regulator must be voltage or current sensitive as required for the specific operation.
3. The transient characteristics of the components may be appreciably underdamped, providing that the frequency of the transient is high, and the damping is adequate. Under such conditions

the oscillation is suppressed quickly and the generator output is not seriously affected.

4. Magnetic amplifiers have a high gain characteristic and are very sensitive to current changes. This makes them very satisfactory as regulator components.

5. An analysis of performance based on frequency response methods is considered practical. The block diagram and approximate linear transfer functions have been derived. Evaluation of these transfer functions and detailed analysis have not been undertaken because of time limitations.

CHAPTER II

THE PROBLEM OF VOLTAGE REGULATION IN ELECTRICAL MACHINERY

The satisfactory voltage regulation of a generator, a motor-generator unit, and a complete system have been the pursuit and efforts of many investigators. This is definitely not a new problem and much has been accomplished in the study of voltage regulation.

The following enclosure from a Bureau of Ships letter to a leading commercial supplier of electrical equipment indicates that the problems of voltage regulation, though old, have not been completely solved.

VOLTAGE REGULATOR PROBLEMS AND LONG RANGE OBJECTIVES

1. The following summarizes our present views on the nature of the long range voltage regulator problems with which the Electrical Branch of the Bureau of Ships is concerned, and of the long range objectives which it hoped we can attain by the solution of these problems. The discussion is in terms of the specific case of d-c to a-c motor generators. It is believed that the results of a solution for this case can be applied without difficulty to generators driven by turbines or diesel engines.

PROBLEMS

2. First problem. The first problem is to find the answer to the following questions;

a. Which machine characteristics of the motor and generator used in a motor generator must be known to permit the design and construction of the voltage regulator before the machines are available to experiment with?

b. How can we measure these characteristics?

c. How closely must the range of permissible values for the machine characteristics be specified in order to avoid the necessity of building an excessive range of adjustment into the voltage regulator?

d. Can the machine designers design their machines with

sufficient accuracy so that we can be sure the machines will actually have machine characteristics within the specified ranges of values?

3. Second problem. The second problem is to find an answer to the following question: Suppose we have definitely specified performance characteristics for a complete unit consisting of d-c motor, a-c generator, voltage regulator, and possibly a speed governor for the motor. Knowing the specified performance characteristics for the complete unit, what values must be specified for the machine characteristics in order to arrive at an optimum design for the complete unit, taking into consideration weight, space, cost, and other pertinent factors for both the machines and the regulator?

4. Third problem. The first two problems are concerned with a motor-generator and regulator to meet specified performance requirements for the complete unit. The third problem goes beyond this and amounts to finding an answer to the following question: What performance requirements should we specify for the combined unit in order to arrive at an optimum design for a complete system which includes motor-generators and the equipment which uses power from the motor-generators?

OBJECTIVES

5. Faster procurement. If we have the answers to questions 2(a) to 2(d), and if the answer to 2(d) is affirmative, the Bureau can specify performance requirements for the complete unit consisting of machines and voltage regulator (and speed governor, if required). The prime contractor for the complete unit can specify the machine characteristics, tell the machine designer to build machines with these characteristics, and tell the voltage regulator designer to design a regulator to work with machines of these characteristics and give the performance specified by the Bureau of Ships for the complete motor generator. Machines and regulators can be built simultaneously and assembled together with complete confidence that the assembly will meet the performance requirements specified for the complete unit. This unit will not, however, necessarily be the optimum design to meet the specified performance requirements. It will do the job, but for the same performance requirements on the complete unit, a different choice of machine characteristics might lead to a different combined unit which would do the job equally well and have advantages with respect to weight, space, or cost.

6. Better motor generator design. If we have the solution to the second problem, we can specify the performance requirements for the complete unit and then be able to specify the machine characteristics which will result in an optimum design for a complete unit to meet the specified performance requirements.

7. Better system design. If we have the answer to the third problem,

we will be able to select the performance requirements for motor generators in such a way as to result in an optimum design for a complete system including motor generators and power utilizing equipment.

8. Simplification and Standardization. Another objective is to simplify and standardize motor generators.

a. A first step would be to tabulate the minimum number of standard building blocks of specified characteristics (motor and generator combinations, voltage regulators, and speed governors) which can be assembled to make all of the motor generators needed by the Navy.

b. The second step would be to tabulate the minimum number of smaller standard building blocks of specified characteristics (motors, generators, and components of voltage regulators and speed governors) which can be assembled in different combinations to make the larger standard building blocks contemplated in the first step.

This group of questions at first glance might appear to be rather formidable. The answer is not obvious to the student but can definitely be determined if given enough time. To give credence to this last statement one need only note the vast advancement in voltage regulation due to the use of various types of regulating devices.

Due to the limited time a student can devote to the thesis research, it was decided to investigate only a small segment of the vast topic of voltage regulation. The specific intent was to study the voltage regulator for a synchronous generator and ascertain the characteristics of the voltage regulator which make it function effectively in conjunction with the synchronous generator.

A five kilowatt - one hundred twenty volt - four hundred cycle motor-generator power supply and associated control equipment was provided by the Bureau of Ships to conduct this investigation. A complete description of the various units and the theory of system operation is appended as Appendix IV.

CHAPTER III

THE METHOD OF ATTACKING THE PROBLEM

The procedure that was followed in attacking the voltage regulation problem was straight forward. The system was adjusted as directed in the instruction book (Bibliography - 10) and tested for normal operation. The operation was normal and the stated ampere and voltage values were realized. In effect, the answer to the chosen regulation problem is here. The remaining problem is to interpret this answer.

The various means of interpretation are:

1. The use of feedback control theory in developing a frequency response analysis. In order to apply feedback theory, a block diagram of the system must be developed and transfer functions derived for each block. As a first approximation linear theory will be used, but it is probable that future extensions to include non linear theory will be required.
2. The performance characteristics of the system to be analyzed must be determined experimentally. Required tests are:
    a. Step function load test to determine the transient response of the system and its components.
    b. Steady state load tests to determine the actual regulation characteristics and also to obtain data for use in transfer function evaluation.
    c. Certain static tests such as the no load saturation curve of the generator.

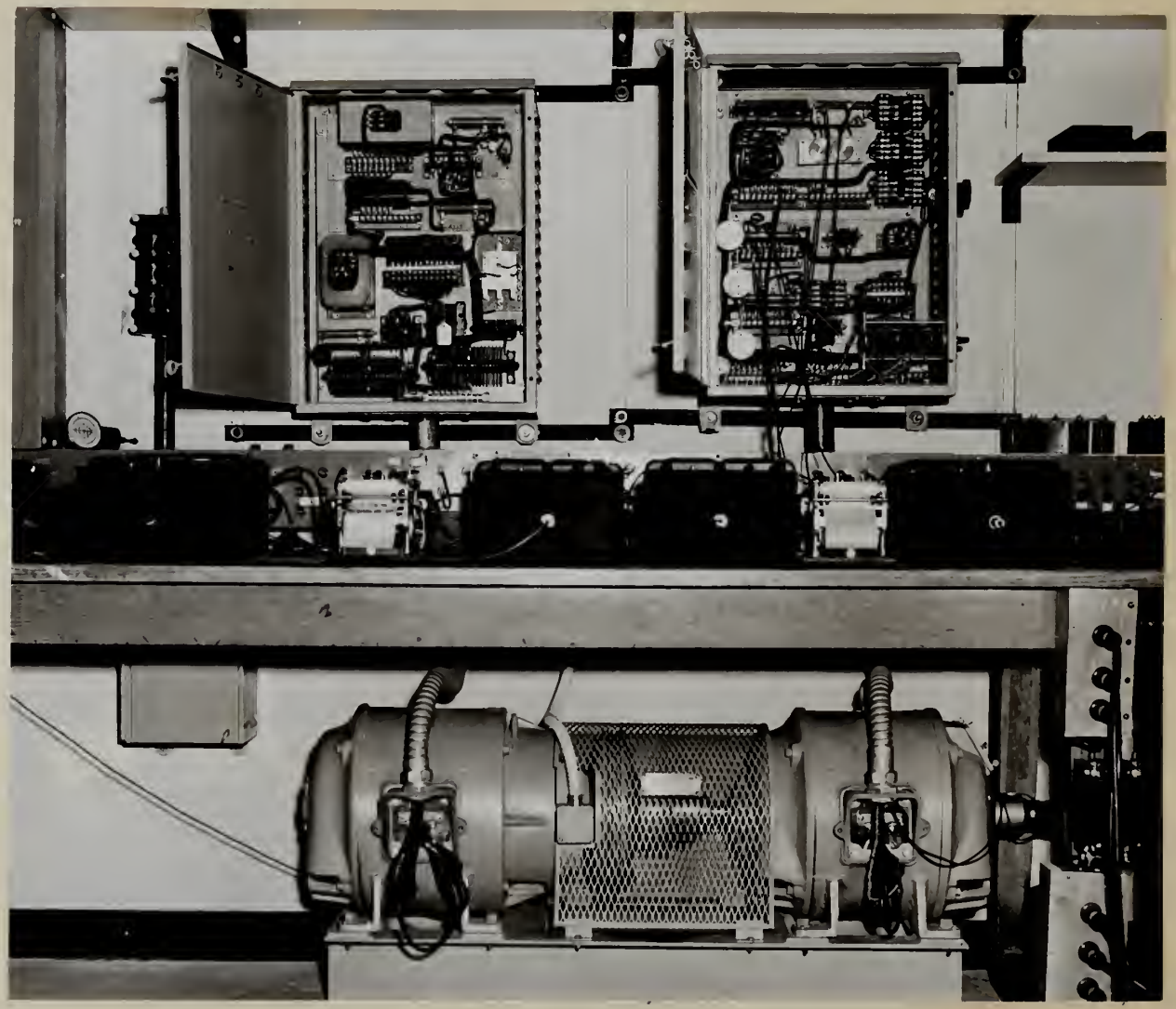
Use of this information will permit correlation of the results with

theoretical analysis.

Photographic techniques will be utilized at the main junctions to determine the wave shape of both the current and voltage. This will further establish the effect of the various components on the input quantities. In addition it will indicate what the true quantity is in relationship to the indication recorded on the meters and recording devices. It will further indicate what corrective action might have to be taken to secure a more desirable characteristic.

Thus no one technique will be used to the exclusion of the other, but all these devices will be used in order to determine the correlation between the theorectical analysis and the actual operation.

Figure 1
page 8



Motor-Generator-Speed and Voltage Regulator System

CHAPTER IV

CONSTRUCTION OF TEST EQUIPMENT AND INSTRUMENTATION

The instrumentation of the motor, clutch, generator, and voltage regulator, was accomplished by utilizing the special distribution buses which were installed to permit rapid, safe, and easy reading of the desired quantities. In addition to the special buses shown in figures 2 , 3 , 4 , and 5 the connector boards in the voltage regulator and the individual components were utilized directly in obtaining the required data.

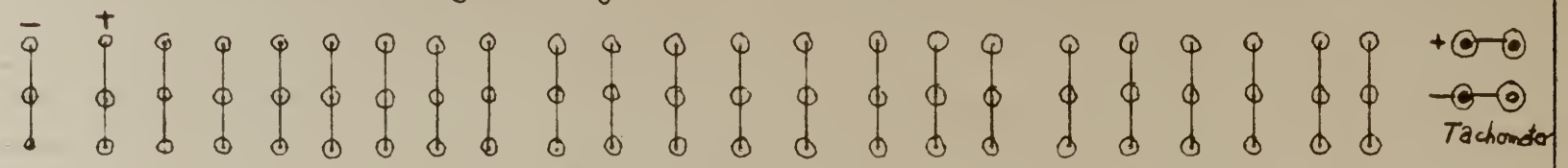
The complete instrumentation of the motor, clutch, generator, and voltage regulator was prompted by the realization that no one unit could be operated so that it was basically independent of any other unit. The operation of any one component is influenced both directly and indirectly by the operation of the other components.

The three line currents and voltages for the induction motor were obtained by inserting a Weston Ammeter (Appendix I-(a)) in each line and a Roller Smith Co. voltmeter (Appendix I-b) across the lines as shown in figure 8 . A special starting switch shown in figure 6 protects the ammeters.

The magnetic particle clutch current and voltage characteristics were obtained by opening terminal (3) (minus) on the speed regulator bus and inserting a Weston D C Ammeter (Appendix I-c) and by putting a Weston D C Voltmeter (Appendix I-d) across terminals (3) (minus) and (4) (positive) on the speed regulator bus.

The three other buses indicated on figure 3 were utilized as follows:

Voltage Regulator Panel Bus Connections

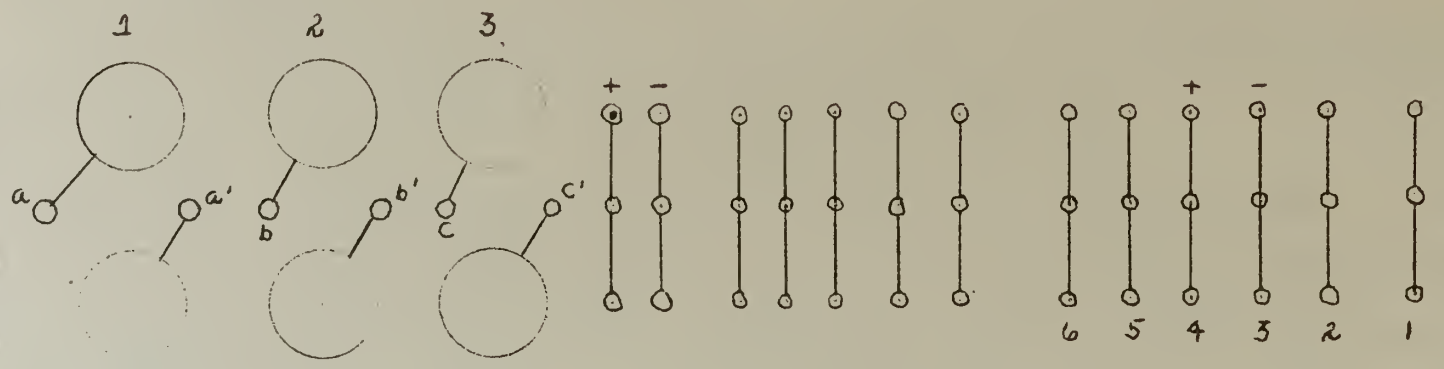


10 9 26 27 28 7 23 1 2 24 3 25 6 16 15 5 8 19 4 14 13 18 17

Buses 10 and 9	DC Excitation For Generator Field
Buses 26, 27, 28	Primary Voltage For Transformer T-1 [27C87-2]
Buses 5, 6, 7	Three Phase Excitation For Final Stage Main Power Full Wave Rectifier
Buses 1, 2, 3	Three Phase Excitation For Primary of Detector Transformer [T1-27C61-2]
Buses 23, 24	Single Phase Excitation For Primary of Transformer T2 [27C61-3]
Bus 25	Connects Line 25 To 3 on Automatic Operation Through Switch S-3
Buses 15, 16	Secondary Voltage Circuit For Transformer T-1 27C49-2
Buses 13, 14	Primary Voltage Circuit For Transformer T-1 27C49-2
Buses 17, 18	Rheostat Control For Manual Voltage Regulation
Bus 19	Permits Reference Voltage To Frequency Sensitive Speed Regulator
Bus 4	Neutral Connection of Wye Connected Tranformer T-1 [27C61-2]
Bus 8	Return Path For Control Current Final Stage To Neutral of Wye Connected Transformer T1 [27C61-2]
Tachometer Bus	Voltage Output From Permanent Magnet Tachometer

Figure 2

Buses For Speed Regulator - Induction Motor and Utility.



Induction Motor Stator Connections

120 V DC

3 ϕ AC 120 V

Spare Bus

Speed Regulator Section

Voltages Between Phases Is Obtained By Reading Across a b; b c; c a;

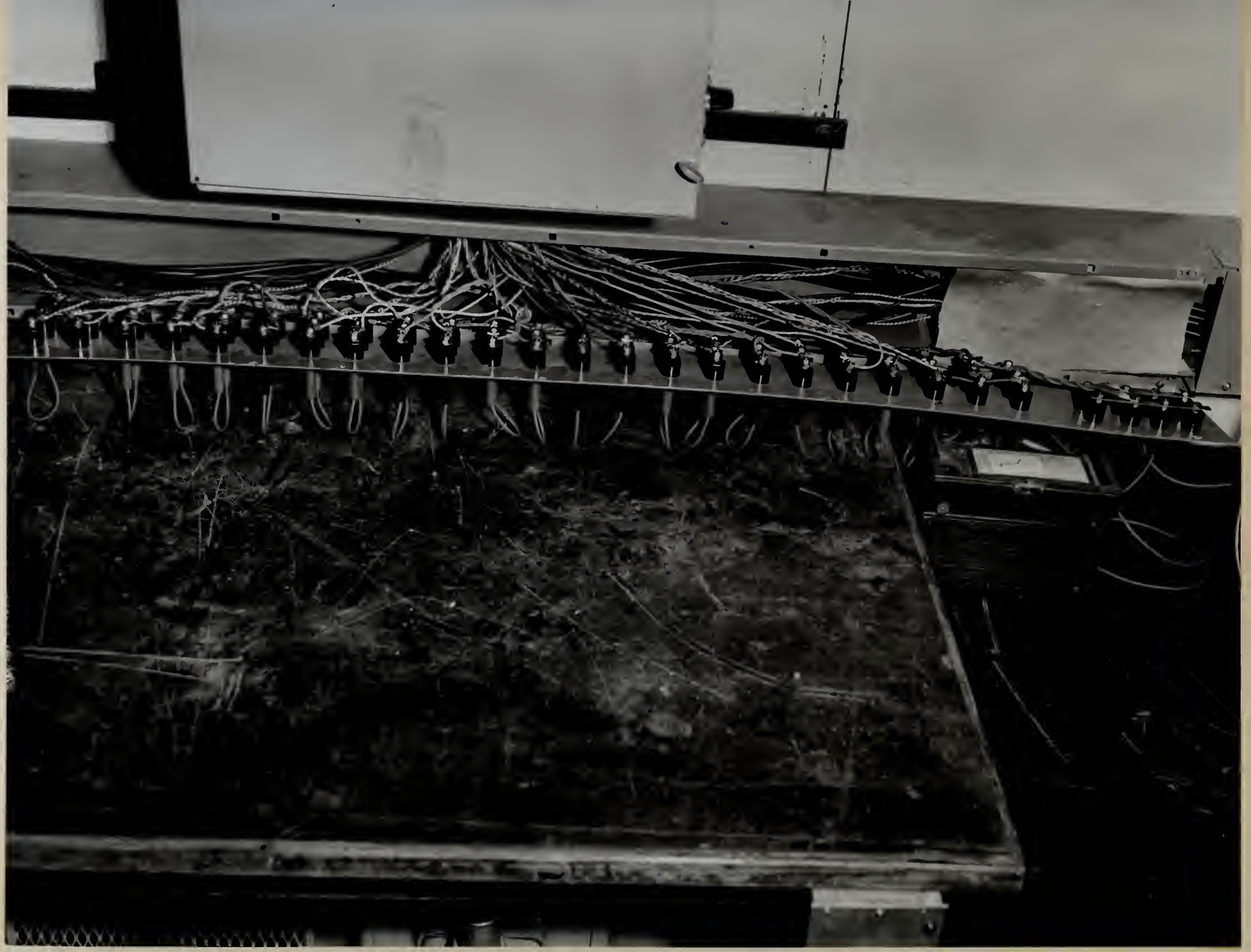
The points a and a' are at the same potential as are b and b' and c and c'.

Bus Six and Bus Five — 440 V - 60 cycle Supply For Initial Excitation For Frequency Control

Bus Four and Bus Three — Direct Current Excitation For The Magnetic Clutch

Bus Two and Bus One — 120 Volt - 400 Cycle For Frequency Control From Phases A1 and A2 of the generator

Figure 3



Physical. Bussing Connections For Voltage Regulator - Internal View.

Physical Bussing Connections For Voltage Regulator - External View

Figure 5
Page 13

120 V - D C: To permit separately excited operation of the generator field.

120 V - 3Ø - A C: To permit using an ungrounded three phase supply for the various recording and indicating instruments.

Spare Bus: This permits trunking in other than the standard voltages or facilitates taking readings from the regulators.

The instrumentation of the voltage regulator was accomplished by opening up all key points and inserting the appropriate ammeters. The desired voltages were also obtained at these key points. The specific instrumentation is as follows:

For the voltage loop in the block diagram figure 19 and 20 .

Transformer T 1-27C61-2:

(1) The primary current was obtained by opening line 4 on T 1-C and inserting a carbon pile resistor and a Weston A C Ammeter (Appendix 1-e).

(2) The primary voltage was read by inserting a Weston A C Voltmeter (Appendix 1-f) between terminals (4) and (3) on the voltage regulator bus.

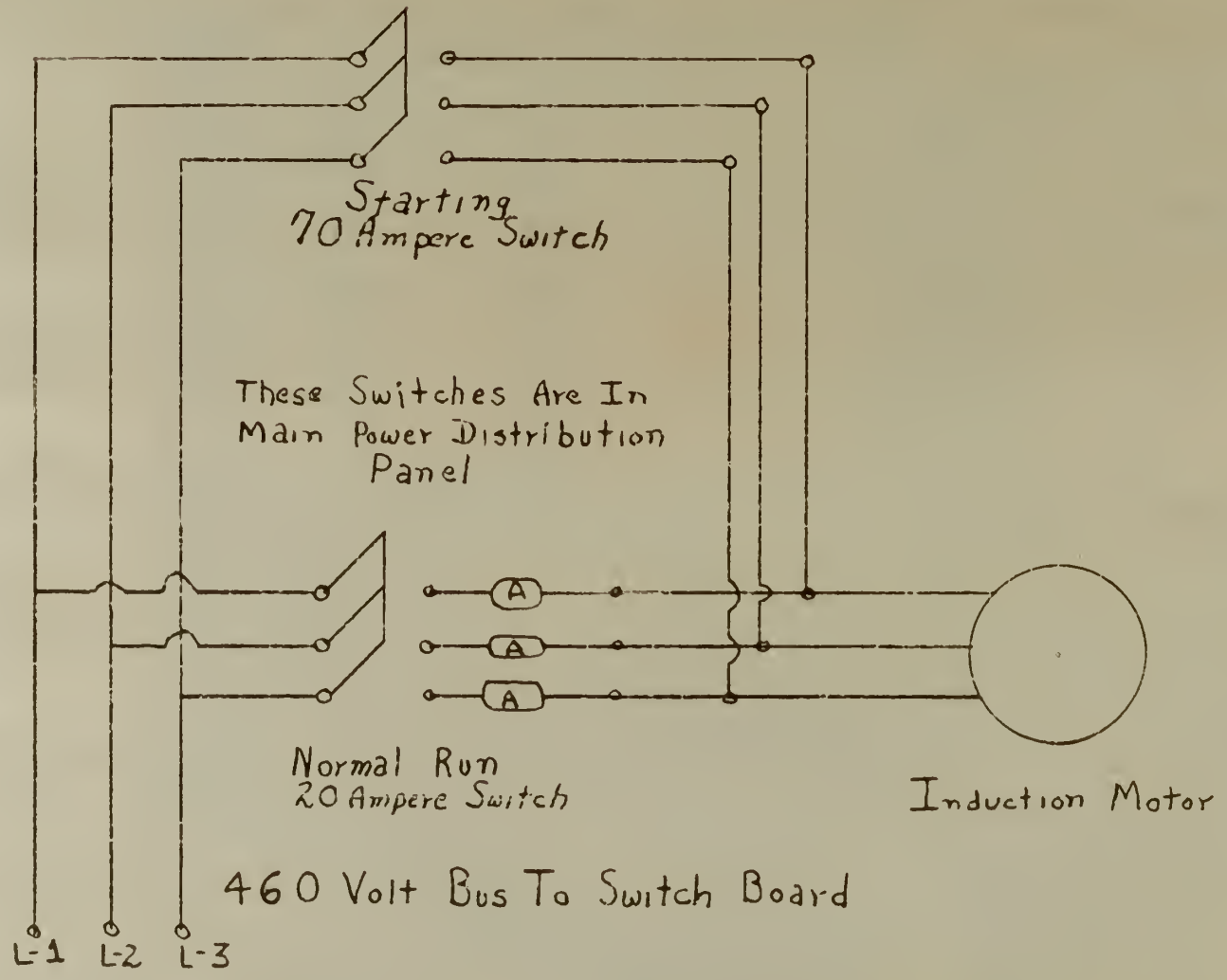
Tripler Reactor L1-38B55-2:

(1) Primary phase (line) current: Opened lead 42 which connects to terminal (11) on voltage regulator panel indicated on figure 14 and inserted a variable carbon pile resistor and a Weston A C Ammeter (Appendix 1-g).

(2) Primary line voltage:

Inserted a Weston A C Voltmeter (Appendix 1-h) between terminals 10 (A1) and 24 (B1).

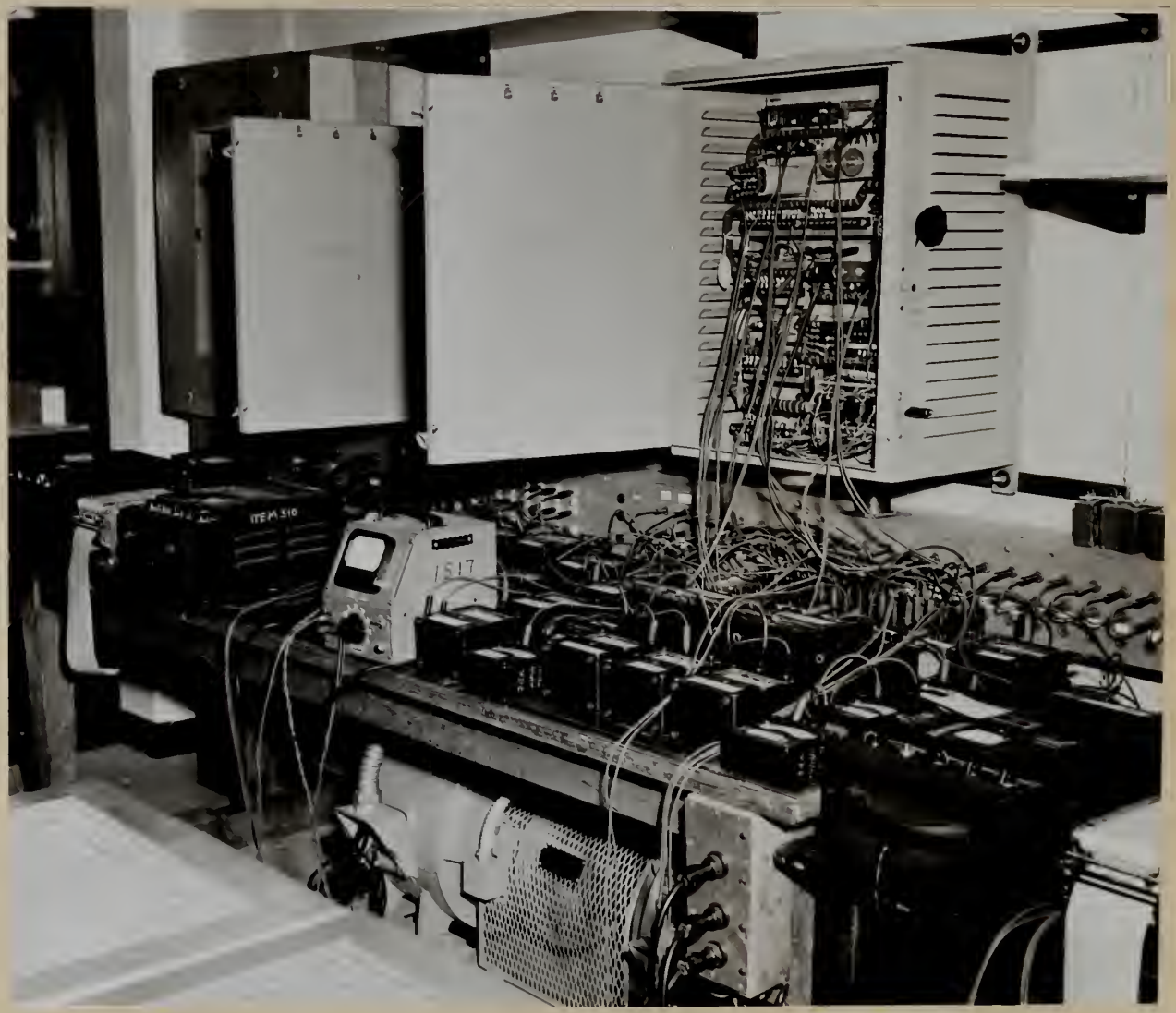
(3) Secondary Current:



Starting and Steady State Switches To Permit Reading Currents In Induction Motor

Figure 6

Figure 7
Page 15-A



Instrumentation of Voltage Regulator

Opened lead 26 (B3) and inserted a variable carbon pile resistor and a Weston A C Ammeter (Appendix 1-i).

(4) Secondary Voltage:

Inserted a Weston A C Voltmeter (Appendix 1-j) between terminals 26 and 27.

Rectifier RECT 1-44B30-2

(1) Output Current:

Opened lead number 45 which joins terminal (7) on the Detector Panel and inserted a Westinghouse D C Ammeter (Appendix 1-k).

(2) Output Voltage:

Inserted a Westinghouse D C Voltmeter between leads 8 and 28 on the rectifier (Appendix 1-l)

Rectifier RECT 1-44C190

(1) Input Current:

Opened lead number 57 which connects to terminal (6) on the Preamplifier Panel 35C63-2 and inserted a Weston A C Ammeter (Appendix 1-m).

(2) Input Voltage:

Inserted a Weston A C Voltmeter between terminals (5) and (6) on Preamplifier Panel 35C63-2 (Appendix 1-n).

Preamplifier 35C63-2 Output (Final Stage Control)

(1) Output Current:

Opened lead 20 which connects to terminal (3) on the Preamplifier Panel and inserted a Weston D C Ammeter (Appendix 1-o).

(2) Output Voltage:

Inserted a Westinghouse Type PX-4 D C Voltmeter between points 11 and 3 on resister R1 (300 ohms) in the Preamplifier Panel 35C63-2 (Appendix 1-p).

Bias Characteristics for Preamplifier 35C63-2

(1) Current:

Opened lead number 12 to resistor R2 (2000 ohms) in Preamplifier and inserted a Weston D C Ammeter (Appendix 1-g).

(2) Voltage:

Inserted a Weston D C Voltmeter between leads 1 and 12 of Resistor R2 (2000 ohms) in Preamplifier (Appendix 1-r).

Total Bias Characteristics - Output of Rectifier RECT 2-44C79-2

(1) Current:

Opened lead 21 which connects to terminal (2) on the Preamplifier 35C63-2 Panel and inserted a variable carbon pile resistor and a Weston D C Ammeter (Appendix1-s)

(2) Voltage:

Inserted between leads (1) and (2) on the Detector Panel 35C124-2 a Weston D C Voltmeter (Appendix 1-t).

Rectifier RECT 1-44C20-2

Input:

(1) Current:

Opened lead 5 which connects to terminal (5) on voltage regulator panel and inserted a variable carbon pile resistor and a Weston A C Ammeter (Appendix 1-u).

(2) Voltage:

Inserted a General Electric A C Voltmeter between terminals (5) and (6) on the voltage regulator panel (Appendix 1-v)

Output:

(1) Current:

Opened lead 48 on Rectifier Unit 44C20-2 and inserted a variable carbon pile resistor and a Weston D C Ammeter (Appendix 1-w).

(2) Voltage:

Inserted a Weston D C Voltmeter between leads 48 and 51 on the Rectifier Unit 44C20-2 (Appendix 1-x).

Final Stage Amplifier Output (Generator Field)

(1) Current:

Opened shorting lead on terminal (9) (plus) of the voltage regulator bus and inserted a variable carbon pile resistor and a Weston D C Ammeter (Appendix 1-y).

(2) Voltage:

Inserted between terminals (9) (plus) and (10) (minus) on the voltage regulator bus a Weston D C Voltmeter (Appendix 1-z).

The three line currents and voltages for the synchronous generator were obtained by inserting appropriate ammeters, voltmeters, and wattmeters as indicated in figure 8 . The lead was three balanced wye connected resistance banks. The specific instrumenting was:

Phase One:

(1) Current - A Weston A C Ammeter (Appendix1-aa)

(2) Voltage - A Weston A C Voltmeter was inserted between points a and c (Appendix 1-bb).

(3) Wattmeter: A Weston Wattmeter was connected as indicated in figure 8 . (Appendix 1-cc)

Phase Two:

(1) Current - A Weston A C Ammeter (Appendix 1-dd)

(2) Voltage - A Weston A C Voltmeter was inserted between points b and c (Appendix 1-ee).

(3) Wattmeter - Connected a Weston Wattmeter as indicated in figure 8 . (Appendix 1-ff).

Phase Three:

(1) Current - Connected a Weston A C Ammeter (Appendix 1-gg).

(2) Voltage - Inserted a Weston A C Voltmeter between points b and a. (Appendix 1-hh).

In order to obtain the speed characteristics of the alternator with stepped load conditions the shaft of the alternator was drilled and tapped to accomodate the shaft of a permanent magnet type generator (Appendix 1-ii). The output of the PM Generator was taken to the tachometer bus on the voltage regulator bus panel.

The instrumentation necessary to secure the transient characteristics of the Tripler Reactor Ll-38B55-2 is shown diagrammatically in figure 9 . The physical arrangement of the equipment is shown in figures 10 and 11 .

In order to facilitate the recording of transient data easily and safely a portable bussing section consisting of nineteen different units of four shorted terminals each was made. Each section was tested using

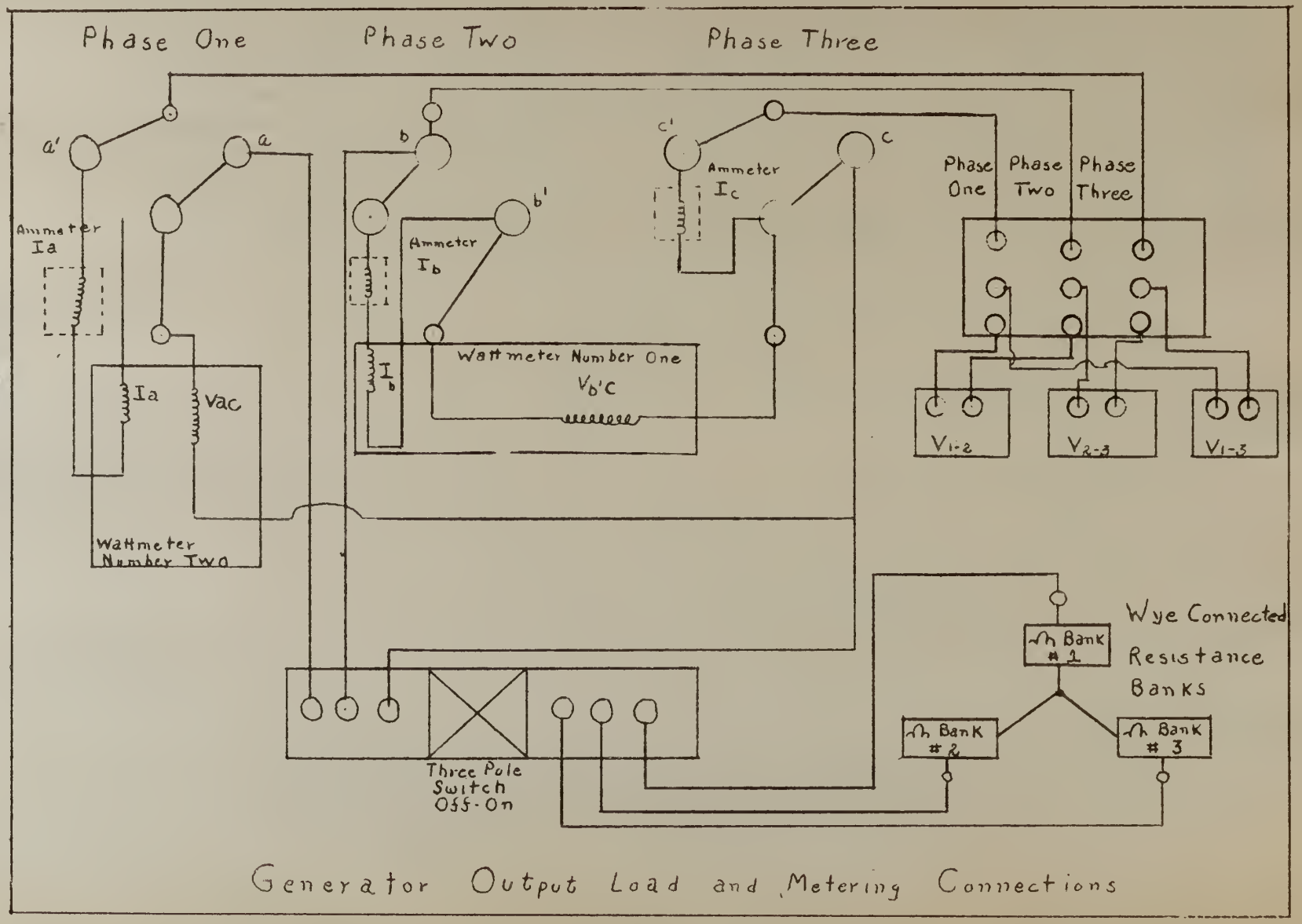
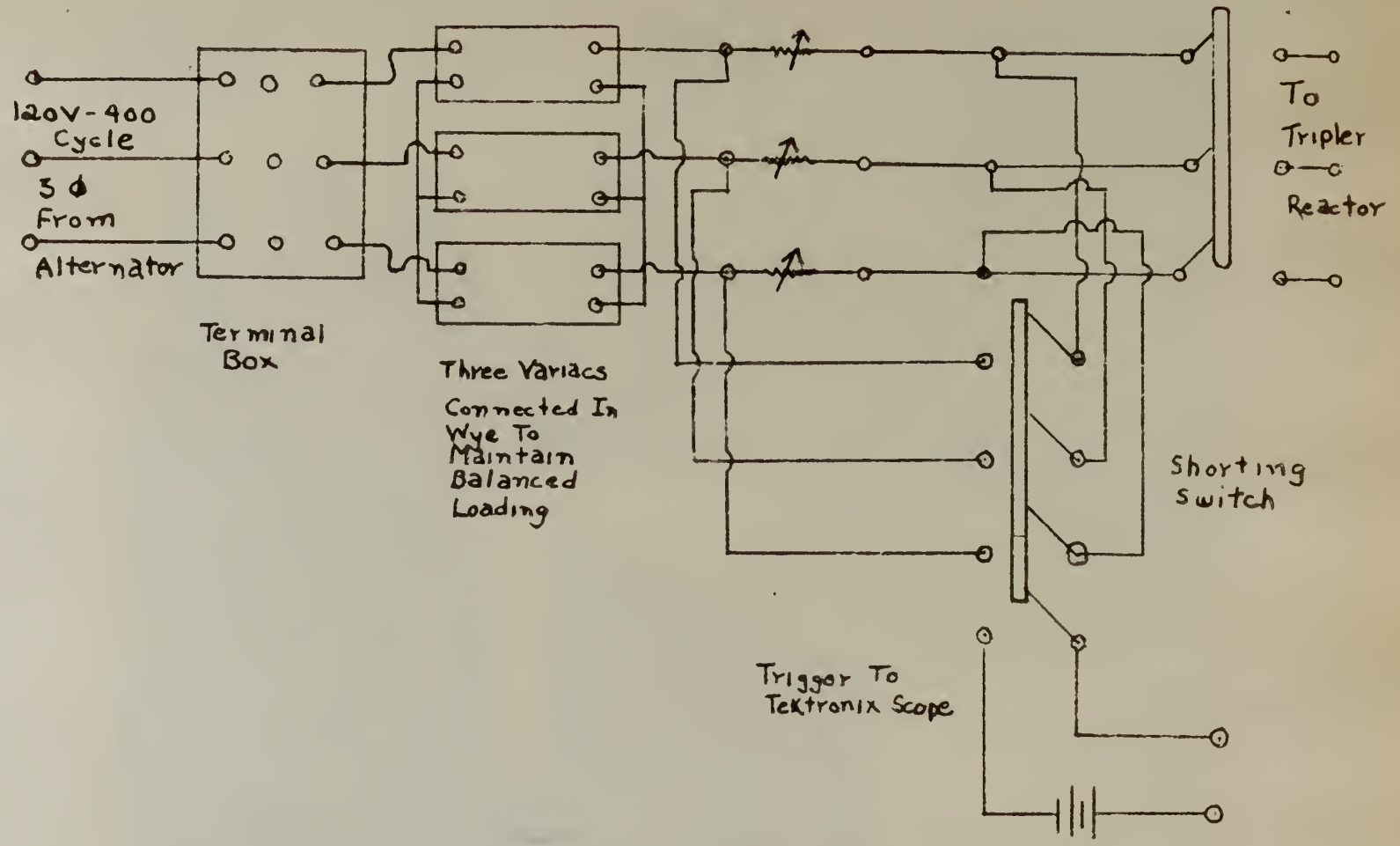
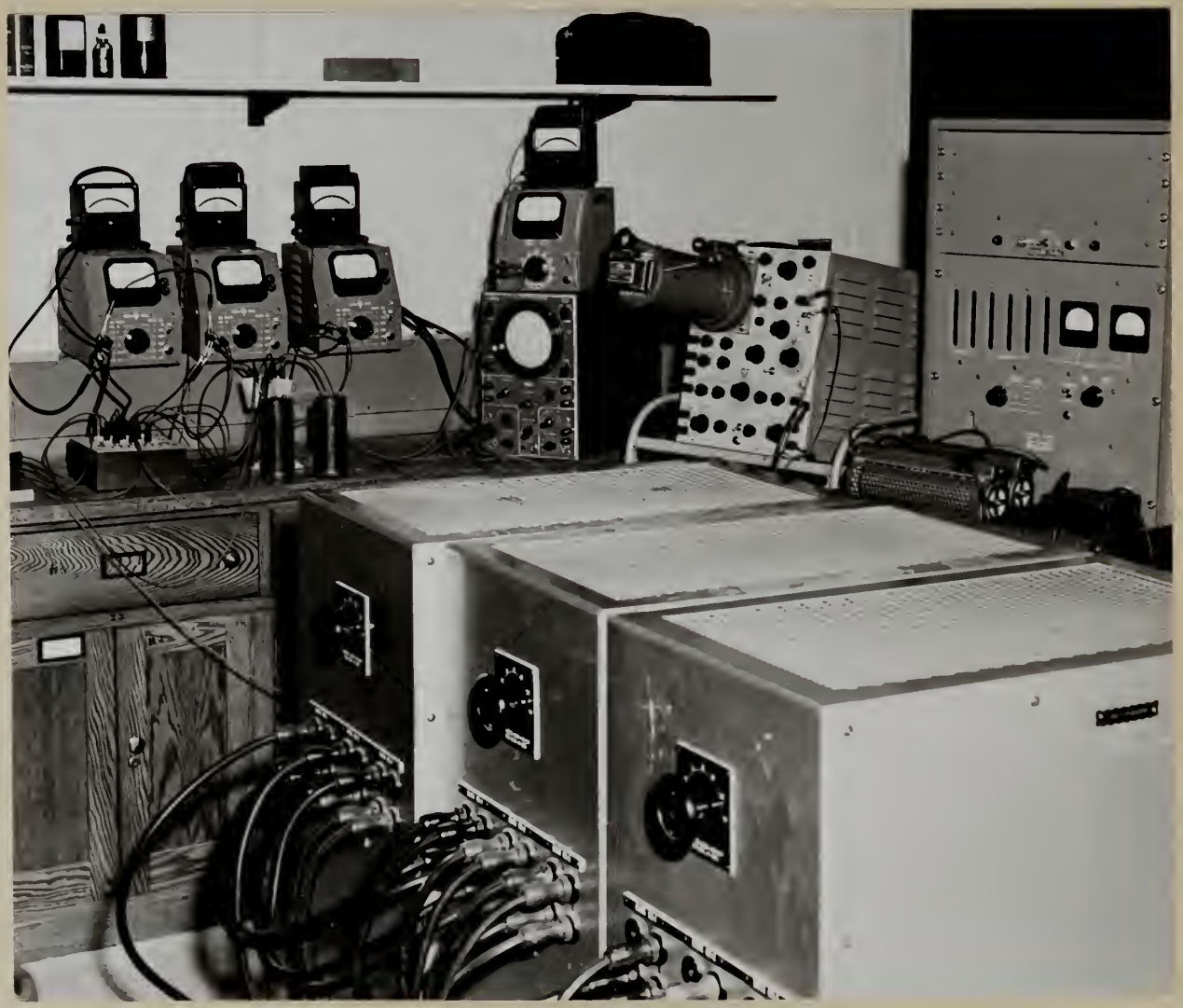

Phase One
Phase Two
Phase Three
a'
a
b
b'
c'
c
Ammeter Ia
Ammeter Ib
Ammeter Ic
Ia
Vac
Ib
Wattmeter Number One
Vb'c
Wattmeter Number Two
Phase One
Phase Two
Phase Three
V1-2
V2-3
V1-3
Three Pole Switch OSS-On
Bank # 1
Bank # 2
Bank # 3
Wye Connected Resistance Banks
Generator Output Load and Metering Connections

Figure 8



Instrumentation To Secure Tripler Reactor Transients

Figure 9



Equipment Utilized To Determine Transient and Steady State Photographic Data

Experimental Equipment To Step Function The Tripler Reactor

Figure 11

a 500 V megger and an ohmmeter thus ensuring proper clearance between terminals and continuity within terminals.

The actual recording of the transient data was accomplished by using the portable bussing section. The desired voltage was applied to the input of the D C amplifier (Appendix 1-jj). The output of the D C amplifier was taken to a Direct Inking Oscillograph (Appendix 1-kk) which recorded permanently and with suitable references the desired transient.

The closest approach to a stepped load condition that could be realized was to use a three pole single throw switch which permitted loading and unloading nearly instantaneously as a first approximation. This switch is shown on figures 1, 5, and 8.

In order to determine the effect of the stepped load current on the entire system the following transients were recorded simultaneously.

(a) Bias Control Circuit:

Voltage between points 1 and 12 of resistor R2(2000 ohms) in Preamplifier 35C63-2.

(b) Preamplifier Control Circuit:

Voltage recorded between points 8 and 28 on the rectifier RECT 1-44B30-2.

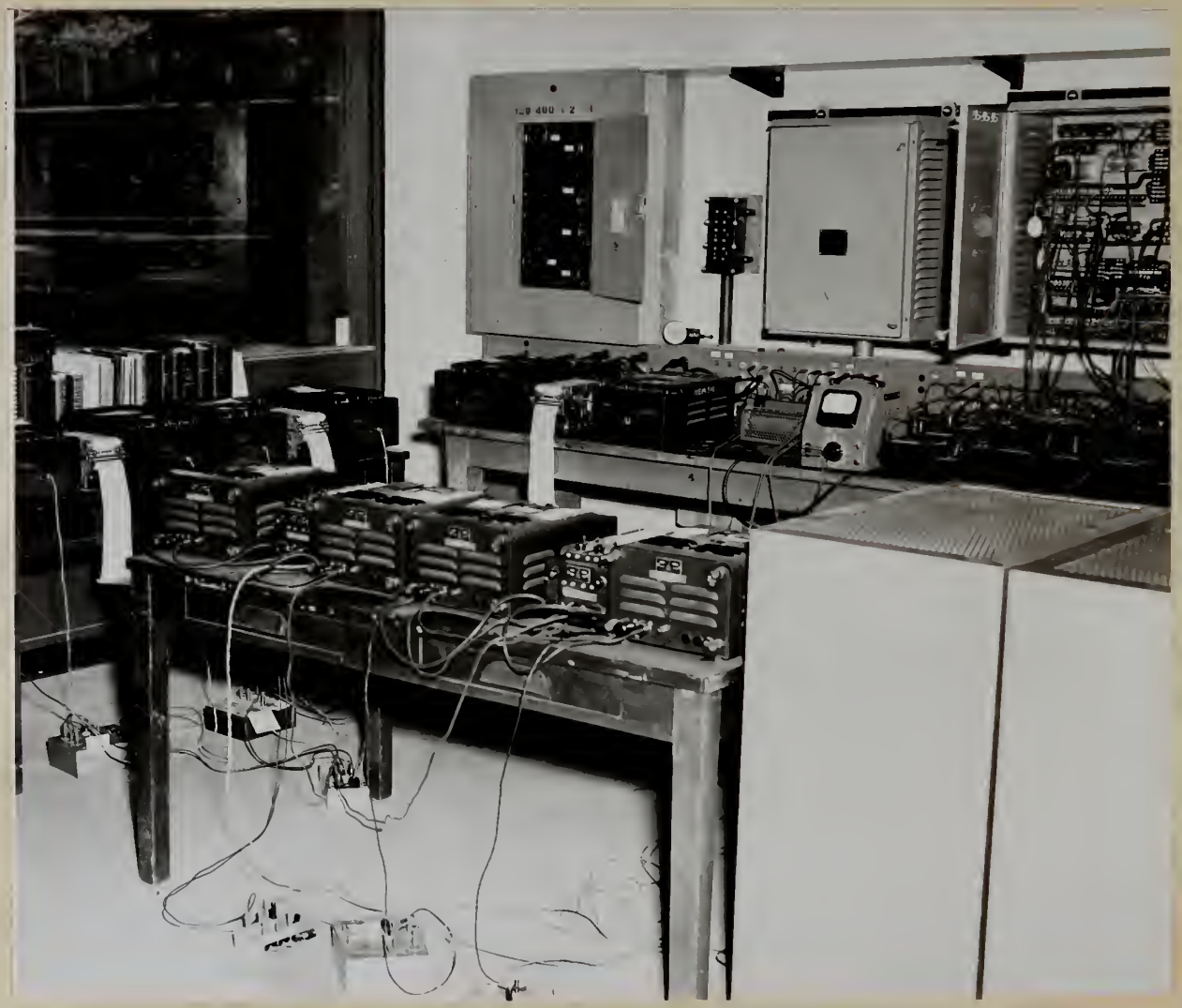
(c) Final Stage Amplifier Control Circuit:

Voltage recorded between points 11 and 3 on resistor R1 (300 ohms) in the Preamplifier Panel 35C63-2.

(d) Final Stage Amplifier Main Power Circuit:

Voltage recorded between leads 48 and 51 on the Rectifier Unit 44C20-2

(e) Generator Field Circuit:



Brush Recorder Set Up For Simultaneously Recording Transients At Key Positions Throughout System

Figure 13
Page 25

Brush Recorder Set Up For Simultaneously Recording Transients
At Key Positions Throughout System

Voltage recorded between terminals (9) (plus) and (10) (minus) on the voltage regulator bus.

(f) Magnetic Particle Clutch Circuit:

Voltage recorded between terminals (3) (minus) and (4) (plus) on the speed regulator bus.

(g) Generator output:

Voltage from PM Generator recorded between terminals on the tachometer section of the voltage regulator bus.

The physical arrangement of the amplifiers and brush recorders is shown in figures 12 and 13.

The same general physical arrangement was utilized in taking the photographic information. The only difference in procedure was to take the voltage drop across a variable carbon pile resistor in order to indicate the current wave shape. The fact that there may be extreme differences is indicated in the comparison of the voltage and current wave shapes in Chapter Six, Analysis of Data.

The photographic data was recorded using a Cathode Ray Oscilloscope (Appendix 1-ll) and an Oscillograph Record Camera (Appendix 1-mm).

To ensure that the frequency of the generator output voltage was four hundred cycles per second, a sample of the output voltage was checked using the Hewlett Packard Frequency Counter (Appendix 1-nn).

CHAPTER V

THE VARIOUS TESTS CONDUCTED

In order to know what might be expected operationally from this voltage regulator system, it was necessary to conduct several tests. The various tests which were conducted are listed below and explained in the following paragraphs:

(1) Calibration of all ammeters and voltmeters.

(2) Self-excitation of the generator field with the voltage regulator operating in automatic.

(3) Self - excitation of the generator field with the voltage regulator operating in manual.

(4) Separate excitation of the generator field with no regulation.

(5) Separate excitation of the generator field with no regulation at the following initial voltages:

80, 100, 120, 140 and 150 volts.

(6) Tachometer voltage output as a reliable reference of alternator speed and voltage.

(7) Tripler Reactor transients

(8) Simultaneous transients at the main positions in the voltage regulator system.

(9) Photographic record of steady state test information.

In order to be assured that the quantity which was being measured was correct, or if this quantity were in error, how much error was involved, all meters were calibrated against the respective secondary standard ammeters, and voltmeters.

The normal operation of the voltage regulator system is in automatic operation. With the voltage regulator system in automatic, the alternator was loaded by means of resistance banks. The results of the loading is indicated in figure 23 .

In order to understand the comparative operation of the voltage regulator in manual operation as opposed to automatic operation, the voltage regulator system operating in manual was loaded using the resistance banks. The results of this test are indicated in figure 23 .

The inherent magnetic properties of the material which are used in this alternator can best be determined by separately exciting the generator field as indicated in figure 22 . There is no loading of the alternator and the regulating equipment is inoperative. The results of this test are shown in figure 22 .

To determine the effect of loading on the alternator which is separately excited and with the regulation equipment inoperative, the generator field was separately excited at various values and loaded. The results of this test are indicated in figure 21 .

In order to have an accurate indication of the alternator terminal voltage and speed changes of the alternator, a Permanent Magnet Generator was installed. The output voltage of the P M Generator was recorded with a Brush recorder.

In order to understand the steady state and transient characteristics of the Tripler Reactor, the steady state and transient tests were conducted with the various results indicated in figures 60 , 61 , 62., 25 , and 53 .

The simultaneous recording of transient or steady state data at the

main junctions in the system when subjected to stepped load conditions will be indicative of the system performance, and also show the inter - relationships existing between the various units.

The use of photographic techniques provides an accurate means of seeing what the specific quantities being utilized are as opposed to their theoretical characteristics.

CHAPTER VI

ANALYSIS OF DATA

A. Derivation of a Proposed Transfer Function Based on experimental data

B. The Significance of the Plotted Graphs Determined from Steady State Values

C. The Significance of the Transient Data

D. The Significance of the Photographic Data

A. Derivation of a Proposed Transfer Function Based on experimental data

This research was conducted using the physical components which are described in detail in Appendix IV and shown in figures 14 and 18. The purpose of this research was to become conversant with the basic characteristics of a voltage regulator and to determine the properties which make it function effectively in conjunction with a synchronous generator. This means that it must be possible to express these characteristics in some manner, such that they are related to a known reference. The procedure that was utilized was the application of linear servomechanism theory (Bibliography 41, 42). This means that it is necessary to devise an appropriate and accurate representation of the system and to be able to represent the various building blocks by a proper expression.

In the determination of the various blocks, it is tacitly assumed that each block is a separate non-interacting unit. Thus the output of one block will be connected to the input of another block; and this second block, when referred to the first block, will have a high impedance.

Throughout this research it has been assumed that the various components have linear characteristics. It will be shown later that this assumption is not totally correct because some of the characteristics deviate slightly from the linear concept. Nonetheless, in order to secure an insight into the system's performance, the linear concept will be utilized.

In figure 14 the overall connections for the voltage regulator with the internal units are shown. Whereas this diagram is important and shows the units which are to be considered only for the voltage

REMOVE JUMPER WHEN PARALLEL OPERATION IS REQ'D.

AUTO. VOLT. ADJ. 35B175-2

T1 27C61-2

T1-A

T1-B

T1-C

T1A

T1B

T1 27C49-2

T2 27C61-3

T1 27C87-2

L1-38855-2

RECT.2 44C79-2

RECT-1 44830-2

DETECTOR 35C124-2

R1 1500Ω

RECT.-1A 44B142-2

RECT.-1B 44B142-2

R1 100Ω

R2 100Ω

MANUAL START 35C64-3

RECT.1A

RECT.1B

RECT.1C

44C20-2

RECT.1A 44C190-2

L2 27C85-2

L1A 38B413-2

L1B 38B413-2

L1-38B366-2

P1 300Ω

R2 2000Ω

R1 150Ω

PREAMPLIFIER 35C63-2

FINAL STAGE 35D96-2

Figure 14

various blocks define the complete system for this investigation.

Next it is necessary to combine these various blocks in such a manner as to arrive at a workable expression. Several reduction procedures could be utilized in order to simplify this diagram as indicated in Bibliography 8,24,27,35,40,41, and 42. It was considered that if any of the other suggested procedures were used then some of the characteristics of the individual components would be masked in a compound expression. Whereas this procedure must be used in solving the mathematical expression relating the generator field current and the alternator line current, it is not utilized in the basic analysis.

The proposed block diagram is shown below. A complete evaluation of the expressions for the various blocks is given in the following paragraphs.

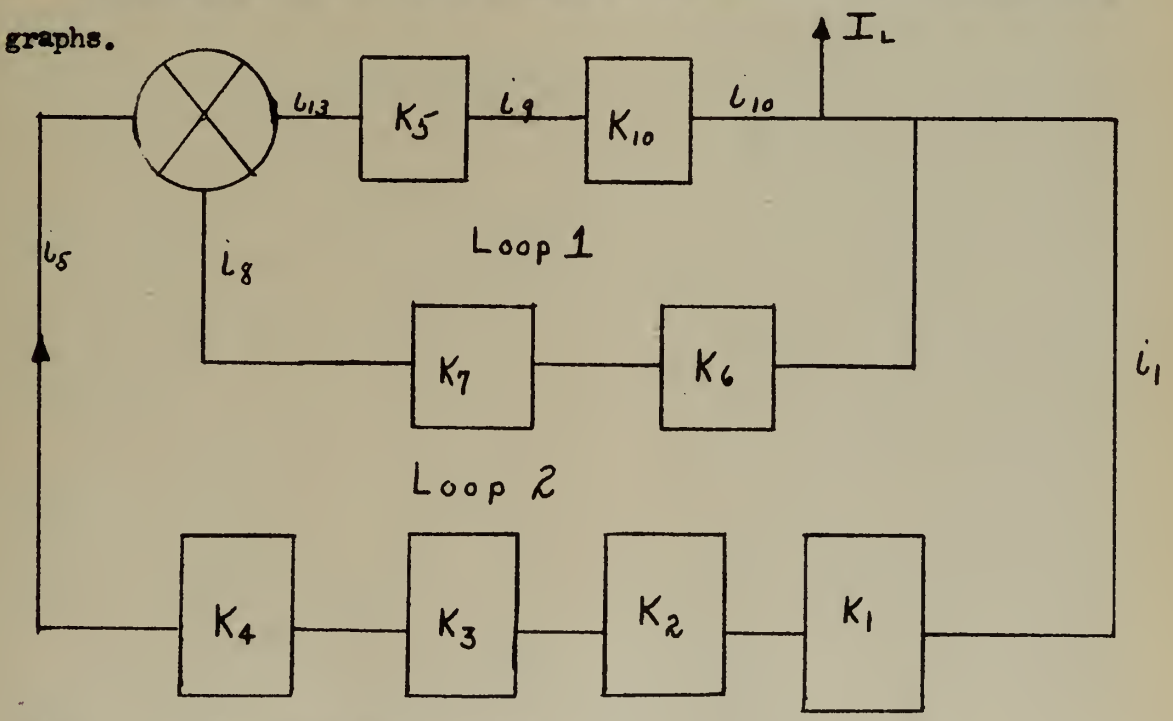


Figure 20-A

Loop 1 - Current Transformer Loop

Loop 2 - Voltage Detector Loop

K 1 - Transformer T - 1(27C61 - 2)

K 2 - Tripler Reactor (L1-38B55-2)

K 3 - Bridge Rectifier (1-44B30-2)

K 4 - Preamplifier (35C63-2)

K 5 - Final Stage Amplifier (L1A-38B413-2) and (L1B-38B413-2)

K 6 - Current Transformer (27C-68-2)

K 7 - Full Wave Rectifier

K 10 - Synchronous Generator

Basic Generator Equations

Voltage Detector Circuit

$$i_5 = i_1 K_1 K_2 K_3 K_4$$

Current Transformer Circuit

$$i_8 = i_6 K_6 K_7$$

Adder in the Final Stage Amplifier

$$i_{13} = i_5 + i_8$$

$$i_{13} = i_1 K_1 K_2 K_3 K_4 + i_6 K_6 K_7$$

Gain Constant in the Final Stage Amplifier

$$i_9 = i_{13} K_5$$

Generator

$$i_{10} = i_9 K_{10}$$

Generator Field

$$E_f = i_f R_f + L \frac{di_f}{dt}$$

$$\bar{E}_f(s) = R_f \bar{I}_f(s) + L s \bar{I}_f(s) - L i_f(0)$$

Transition from Field Current to Generated Voltage

$$\bar{E}_g(s) = K_{gf} \bar{I}_f(s)$$

$$E_g = K_{gf} i_f$$

Generated Voltage

$$E_g = [\vec{R}_a + \vec{L}_{syn}]\, i_a + E_T$$

$$E_g = \left[R_a i_a + L_{syn} \frac{di_a}{dt}\right] + \left[R_L i_a + L_a \frac{di_a}{dt}\right]$$

$$\bar{E}_g = [R_a + R_L]\, \bar{i}_a(s) + [L_{syn} + L_a]\, s\, \bar{i}_a(s) - [L_{syn} + L_a]\, i_a(0)$$

$$K_{gf}\, \bar{i}_f(s) = [R_a + R_L]\, \bar{i}_a(s) + [L_{syn} + L_a]\, s\, \bar{i}_a(s) - [L_{syn} + L_a]\, i_a(0)$$

$$\therefore \bar{i}_f(s) = \frac{[R_a + R_L]}{K_{gf}}\, \bar{i}_a(s) + \frac{[L_{syn} + L_a]}{K_{gf}}\, s\, \bar{i}_a(s) - \frac{[L_{syn} + L_a]}{K_{gf}}\, i_a(0)$$

The general form for the output versus input of a feedback loop is:

$$\frac{\bar{i}_{10}}{\bar{i}_5} = \frac{K_5\, K_{10}}{1 + K_6\, K_7\, K_5\, K_{10}}$$

These K's refer to the K's shown in the block diagram figure 20A.

The Transfer Functions For Various Components

K_5 = Pure gain constant

$$K_7 = \frac{1}{[1 - K_0 C]}$$

$$K_6 = \frac{S\{S[L_1 L_2 i_2(0) - M^2 i_2(0)] + [R_1 L_2 i_2(0) + R_1 M i_1(0) - M]\}}{S^2[L_2 L_1 i_1(0) - M^2 i_1(0)] + S[R_2 L_1 i_1(0) + R_2 M i_2(0) + L_2] + R_2}$$

$$K_{10} = \frac{\bar{i}_{10}}{\bar{i}_9} = \frac{K_9 f}{[R_t + L_t S]}$$ for zero initial conditions

$$K_{10} = \frac{\bar{i}_{10}}{\bar{i}_9} = \frac{K_9 f}{R_t + L_t S} + \frac{L_t \bar{i}_{10}(0)}{i_9}$$ but $i_{10}(0) = 0$ at time $t = 0$

$$K_{10} = \frac{\bar{i}_{10}}{\bar{i}_9} = \frac{K_9 f / R_t}{1 + \frac{L_t S}{R_t}} = \frac{K_9 S / R_t}{1 + \tau_1 S}$$ where $\tau_1 = \frac{L_t}{R_t}$

Now simplifying the above functions

$$K_5 = K_5$$

$$K_7 = K_7$$

$$K_6 = \frac{S\,[\,S(a) + b\,]}{S^2(a) + S(c) + D}$$

$$K_{10} = \frac{K_{gf}}{R_t + L_t S}$$

hence
$$W_1(S) = \frac{\dfrac{K_5 K_{gf}}{[R_t + L_t S]}}{1 + \left\{\dfrac{S\,[S(a)+b]}{S^2(a) + S(c) + d}\right\}\{K_7\}\{K_5\}\left\{\dfrac{K_{gf}}{R_t + L_t S}\right\}}$$

$$W_1(S) = \frac{[\,S^2 a + Sc + d\,][K_5 K_{gf}]}{[S^2(a) + S(c) + D][R_t + L_t S] + S\,[S(a)+b][K_7][K_5][K_{gf}]}$$

Now simplifying

$$W_1(S) = \frac{S^2 M_1 + S M_2 + M_3}{S^3 N_1 + S^2 N_2 + N_4}$$

It is known from the oscillegraphic data shown in figure 57 that the input current is not a true step but consists of a D C current with a small A C ripple riding on the D C. For a first approximation, the ripple may be neglected and the input current treated as a true D C step.

$$\bar{i}_{10}(s) = \bar{i}_{s}(s)\ W_1(s)$$

$$= \bar{i}_{s}(s)\ \frac{s^2 M_1 + s M_2 + M_3}{s^3 N_1 + s^2 N_2 + s N_3 + N_4}$$

but $$\bar{i}_{s}(s) = \frac{A}{s}$$

$$\therefore\ \bar{i}_{10}(s) = \frac{s^2 M_4 + s M_5 + M_6}{s\left[s^3 N_1 + s^2 N_2 + s N_3 + N_4\right]}$$

To determine the expression for load current I_{10} as a function of time, it is necessary to take the inverse Laplace Transform of $\bar{I}_{10}(s)$. Now if

$$F(s) = \frac{s^2 + a_1 s + a_0}{s\left[s + \alpha\right]\left[s^2 + \beta^2\right]}$$

Then f (t) will be expressed as

$$\frac{a_0}{\alpha\beta^2} - \frac{\alpha^2 - a_1\alpha + a_0}{\alpha(\alpha^2+\beta^2)} e^{-\alpha t} - \frac{1}{\beta^2}\left[\frac{(a_0-\beta^2)^2 + a_1^2\beta^2}{a^2+\beta^2}\right]^{1/2} \cos[bt+\psi]$$

where $\psi \triangleq \tan^{-1}\frac{a_1\beta}{a_0-\beta^2} - \tan^{-1}\frac{\beta}{\alpha}$

It must be noted that time did not permit complete evaluation of the proposed transfer function. The following paragraphs indicate methods which may be used to obtain numerical values for the algebraic expressions previously derived. The expressions for the units is shown, and the limitations, if any, which are imposed.

The voltage responsive loop has a change of 0.633 milliamps in the control field of the preamplifier for every volt change in the alternator voltage.

This represents a first approximation whereas the true value will differ from this because the transfer function of the tripler reactor is not a pure gain constant.

Thus the expression for the detector transformer, tripler reactor, and

the bridge rectifier may be expressed as a linear function.

Transformer - T1-27C61-2

$$K = \frac{4}{5}$$

Tripler Reactor - L1-38B-55-2

For verbal discussion see derivation in Appendix .

$$W_{t(S)} = \frac{S\{S[L_1 L_2 i_2(0) - M^2 i_2(0)] + [R_1 L_2 i_2(0) + R_1 M i_1(0) - M\square]\}}{S^2[L_2 L_1 i_1(0) - M^2 i_1(0)] + S[R_2 L_1 i_1(0) + R_2 M i_2(0) + L_2] + R_2}$$

$$\Delta V_2 = \frac{2.5}{3.0} \Delta V_1$$

Rectifier 1-44B30-2

$$\Delta I = \frac{19}{20} \Delta V$$

It is believed that the straight forward servomechanism transfer function approach is not the most suitable nor accurate consideration. It is further believed that the better approach would be to work on incremental changes about the no load operating point and derive the functions on this basis.

The transfer function for the bias rectifier, three phase full wave;

2-44C79-2 is not a pure gain constant as for the main power final stage winding rectifier. It is to be noted that the bias current does not change until the load current has exceeded 140% full lead value. Therefore, the bias winding is assumed constant and neglected in the basic closed loop diagram transfer function computations.

The current transformer (27C-68-2) transfer function will be of the form

$$W(S) = \frac{S\left[S(L_1 L_2 i_2(0) - M^2 i_2(0) + (R_1 L_2 i_2(0) + R_1 M i_1(0) - M\right]}{S^2\left[L_2 L_1 i_1(0) - M^2 i_1(0)\right] + S\left[R_2 L_1 i_1(0) + R_2 M i_2(0) + L_2\right] + R_2}$$

The main power rectifier 44C20-2 Final Stage transfer function can be expressed as a pure gain constant for the range from no load to approximately 130% of full lead value. The computed gain is:

$$\frac{\Delta I_o}{\Delta I_{in}} = \frac{0.0625}{0.210} = 0.298$$

$$\Delta I \text{ output} = 0.298\, \Delta I \text{ in}$$

The Final Stage Amplifier is assumed as a first approximation to be a pure gain constant. From the test data the gain is assigned a value of

$$K = \frac{[0.6][2.5] \text{ millamps}}{[1.3][0.05] \text{ amps}}$$

$$K = 43.3$$

The transfer function for the generator will be of the form

$$W(S) = \frac{K_{gf}}{[R_t + L_t S]} = \frac{K_{gf}/R_t}{\left[1 + \frac{L_t}{R_t} S\right]} = \frac{K_{gf}/R_t}{[1 + \tau_1 S]}$$

The final expression for load current as a function of the generator field current will be expressed as

$$\bar{I}_{load} = \bar{i}_f \; W_2(S)$$

$$= \bar{i}_f \frac{S^2 M_1 + S M_2 + M_3}{S^3 N_1 + S^2 N_2 + S N_3 + N_4}$$

$$\text{Now } \bar{I}_{load} = \frac{A}{S} W_2(S)$$

$$\text{hence } \bar{I}_{load} = \frac{S^2 M_4 + S M_5 + M_6}{S[S^3 N_1 + S^2 N_2 + S N_3 + N_4]}$$

where the coefficients in the numerator consider the effect of the step.

Now $i_{load}(t) = L^{-1}\left[\bar{i}_{load}(s)\right]$

The solution of the lead current as a function of time is not as formidable as it might appear to be at first glance. The determination of the roots of the cubic equation is given in Appendix III. A complete explanation of the solution of a cubic equation is given in H. B. Fine's COLLEGE ALGEBRA (Bibliography 14). However other suitable and desirable procedures are set forth in Bibliography 13 and 33.

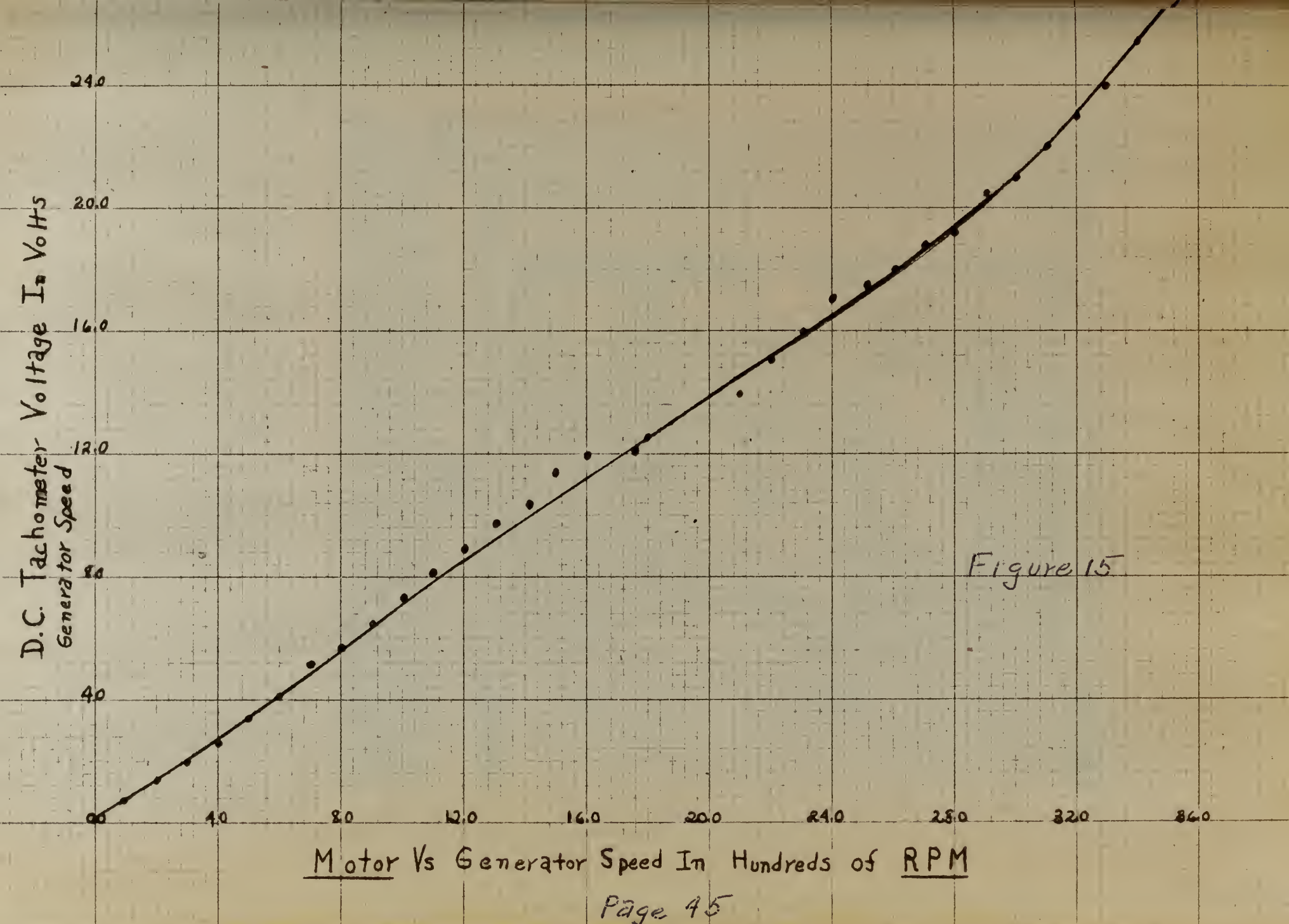
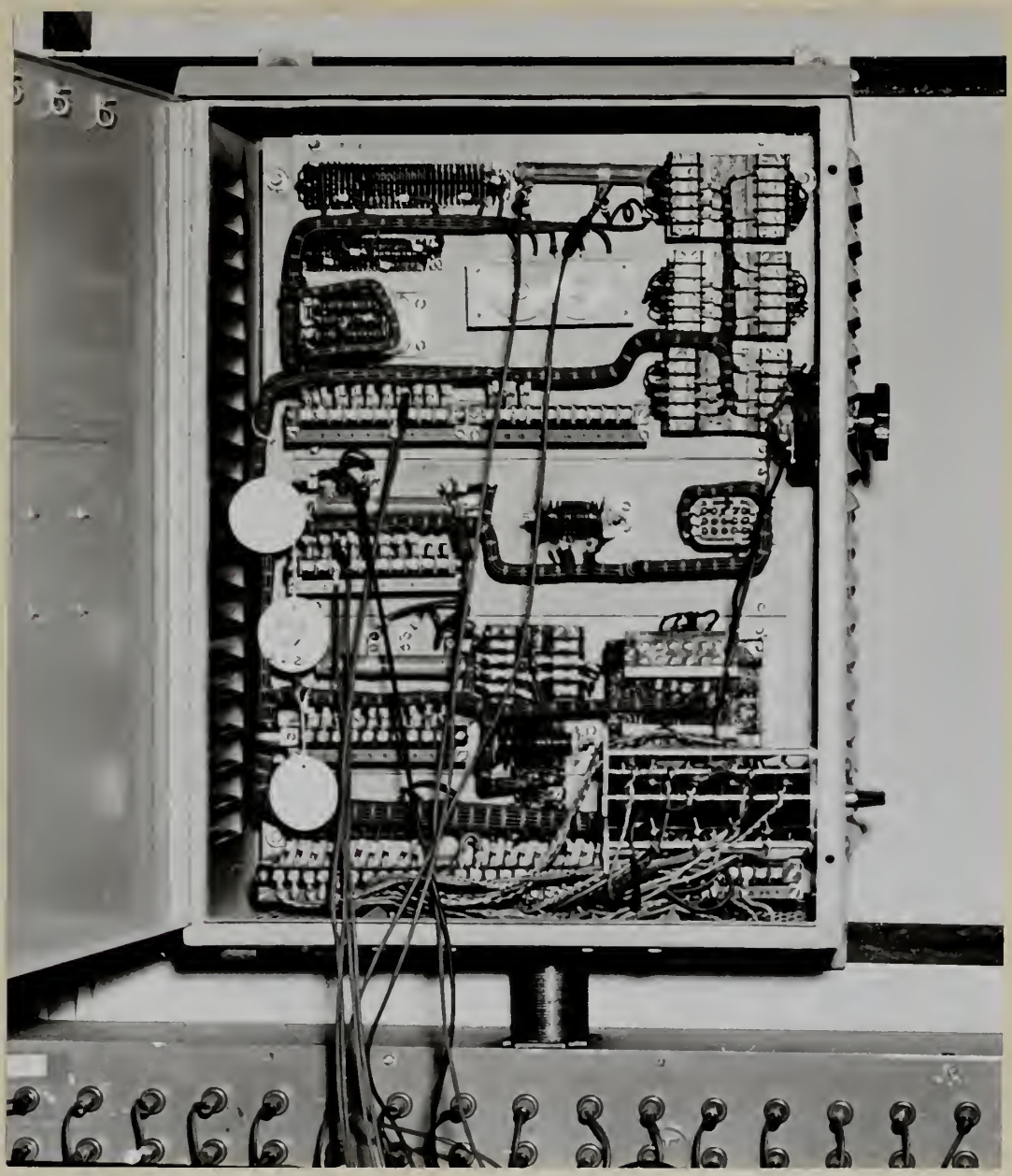

D.C. Tachometer Voltage In Volts
Generator Speed
24.0
20.0
16.0
12.0
8.0
4.0
00
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
Motor Vs Generator Speed In Hundreds of RPM

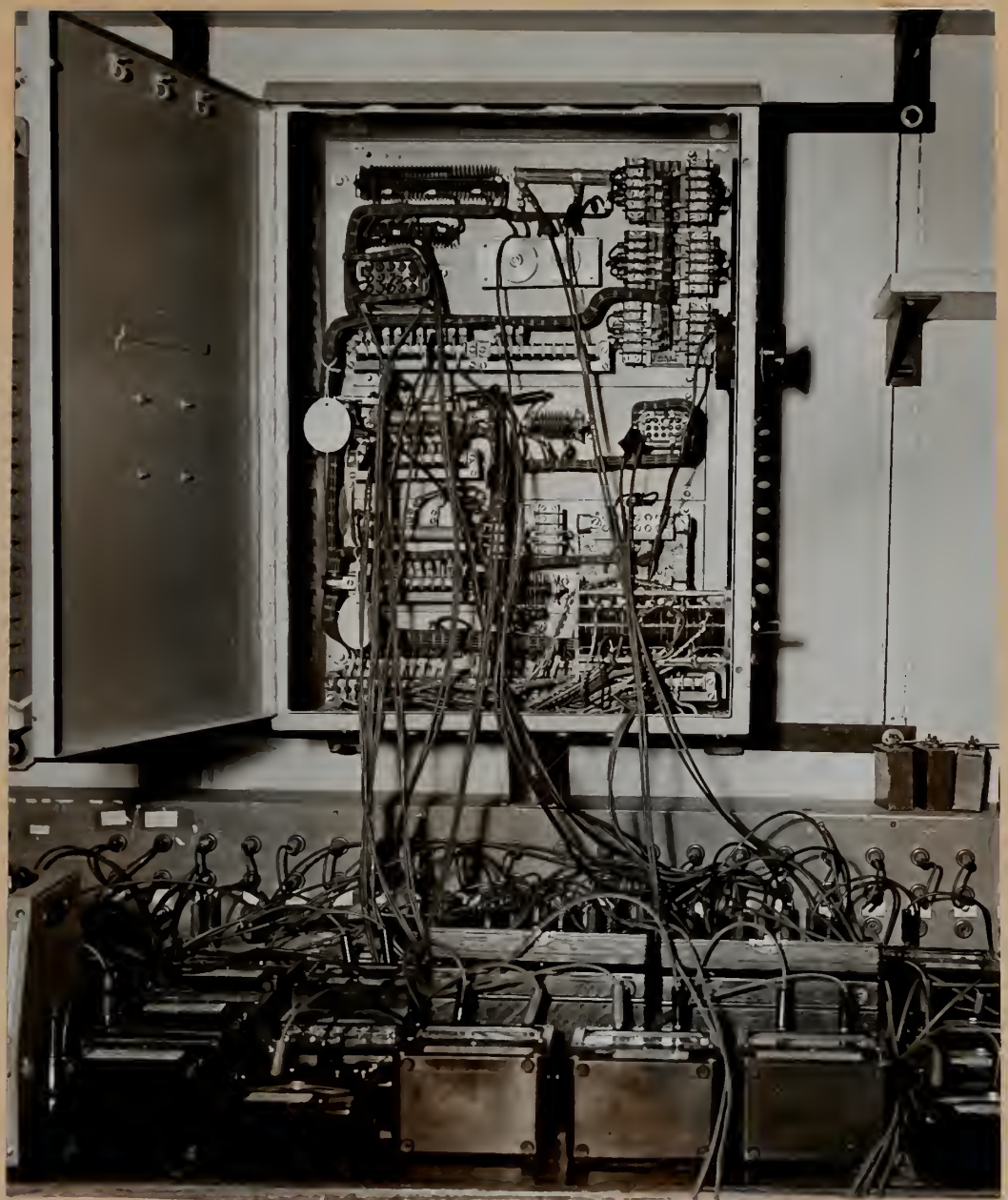
Figure 15



Voltage Regulator

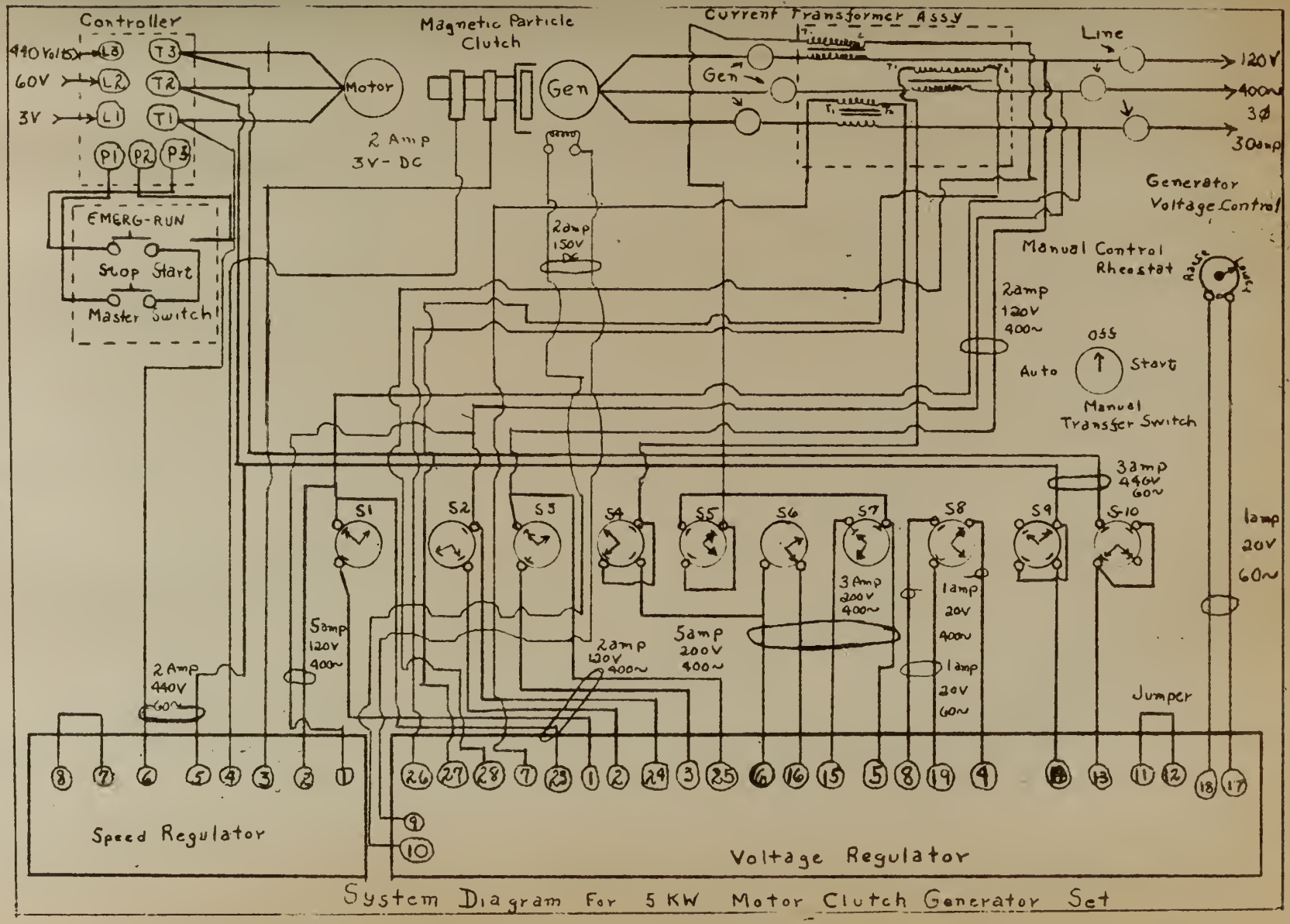
Figure 16

Page 46



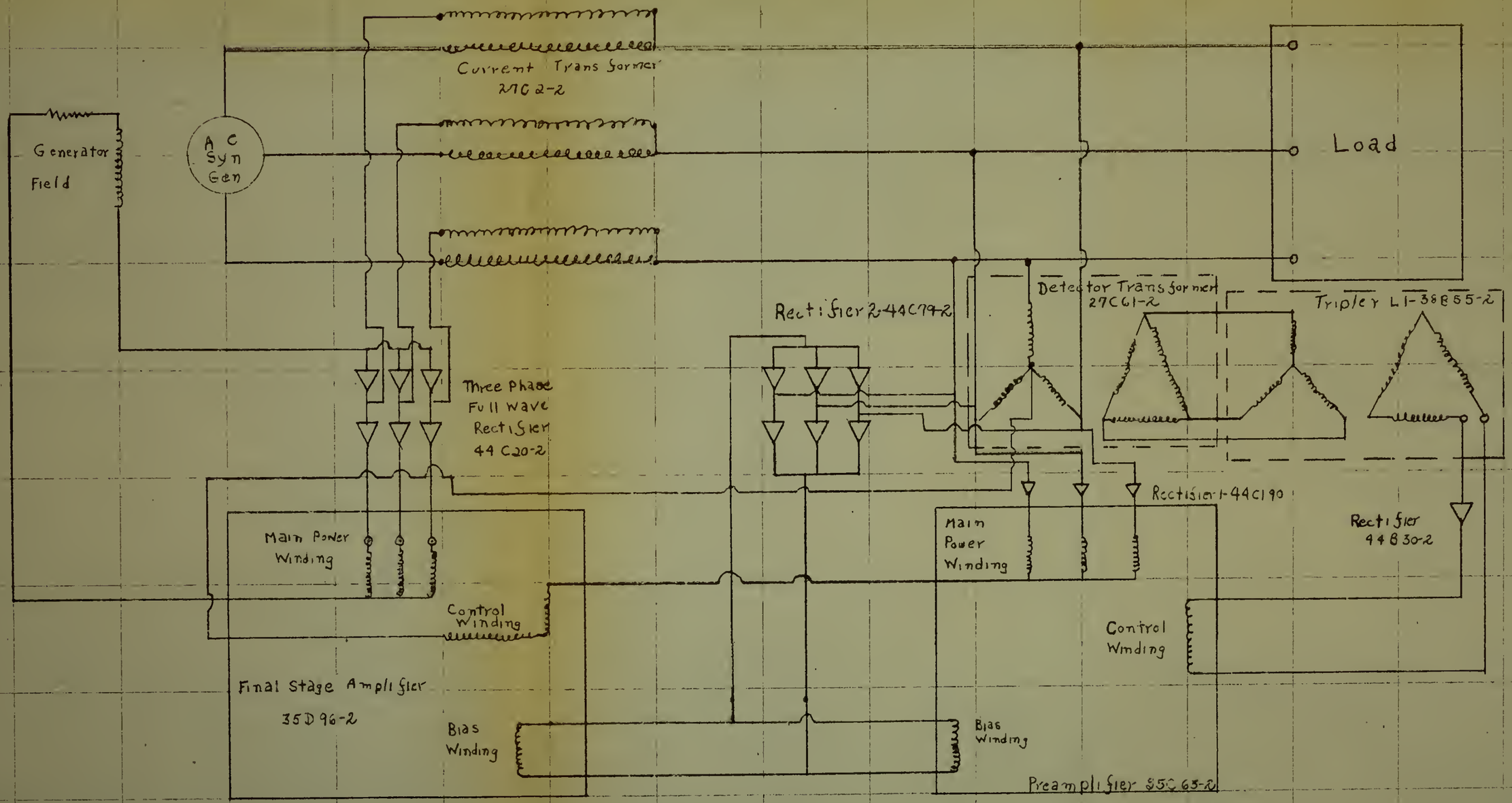
Voltage Regulator Instrumentation

Figure 17
Page 47



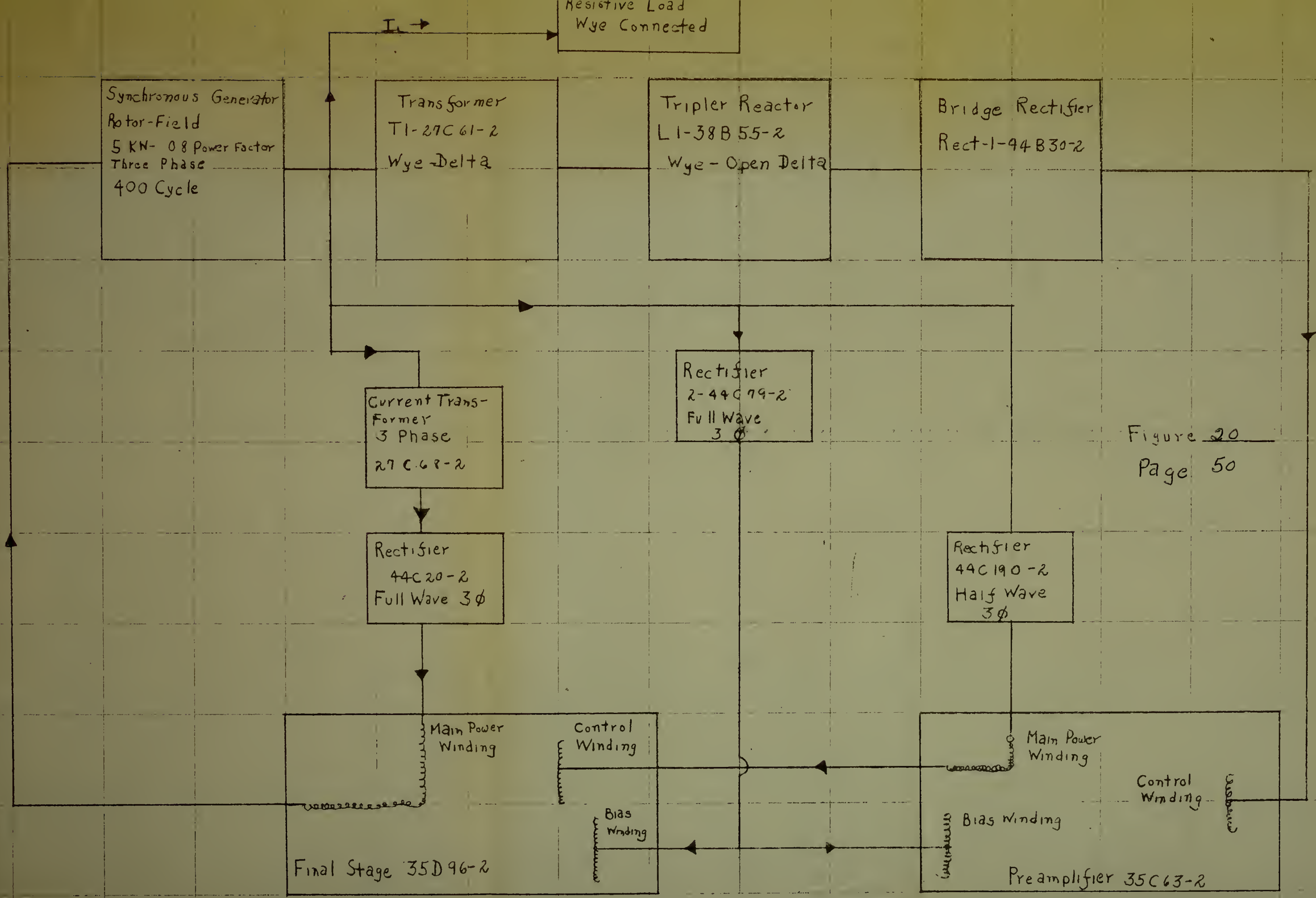
System Diagram For 5 KW Motor Clutch Generator Set

Figure 18



Schematic Diagram of Voltage Regulator and Synchronous Alternator

Figure 19
Page 49



Schematic and Block Diagram For Voltage Regulator System

Figure 20

B. The Significance of the Plotted Graphs Determined from Steady State Values.

The voltage regulator system as defined in the Derivation of the Transfer Function consists only of physical elements. Therefore, it is necessary that the characteristics of these components be determined in order to know how the components function.

The main purpose of the voltage regulator is to maintain the terminal voltage of the synchronous alternator at a preset value.

This tacitly implies that one knows how the synchronous alternator functions independently of the voltage regulator when load is applied. This information was obtained by separately exciting the generator field. Different initial values of excitation were used ranging from 39.5 volts to 81.5 volts which corresponds to synchronous alternator terminal voltages of 80 volts to 140 volts. This information is plotted in Figure24.

As the designed terminal voltage is 120 volts A C, we are mainly concerned with the curve originating at 120 volts A C generator terminal voltage and zero load current.

It is seen that with the application of load the terminal voltage deviates from the desired 120 volts. The percent regulation inherent in the synchronous Alternator at normal 120 V ac initial voltage is:

$$\% \text{ Regulation } \frac{\text{Voltage No Load - Voltage Full Load}}{\text{Voltage Full Load}}$$

$$\frac{120 - 102}{102} \quad \frac{18}{102}$$

$$17.65\%$$

Now if the terminal voltage is to be maintained at 120 volts from no

load to full load or at any specified value, this means that the generator field current must be increased enough to compensate for the drop which is inherent in the synchronous alternator. This in effect is what the voltage regulator must do.

Some further observations about this alternator are definitely in order. It could easily be operated at terminal voltages both higher and lower from the designed 120 volts ac. This assumes that the system which this alternator supplies is able to operate at either the reduced or raised voltage. If this is true, and the voltage regulator should become inoperative in either automatic or manual operation, then the generator field could be self excited to a higher generator field voltage to give the desired terminal voltage under varying load conditions.

The basic curve which is most informative is the magnetization curve, Figure 22 . It is to be noted that for normal operation which is a generator field current of 1.22 amps, for no load, to 1.43 amps, for full load current, the region of operation is just below the knee of the curve. The selection of this region for operation is felt to have been dictated by two reasons.

(1) As the field current is increased from the no load operating point, there is a sufficient increase in terminal voltage. However, if the operating region were shifted to the right, it would require a much larger change in generator field current to secure an equal change in terminal voltage with respect to the designed operating region.

(2) The second consideration, which very likely determined the region of operation of the generator field current, was the factor of hot spot temperature in the synchronous alternator. If the maximum air

gap flux density were increased, it could well mean that the flux densities within the teeth would be abnormally high, thus causing the creation of excessive hot spot temperatures, which could endanger the alternator

Other factors may also enter into the choice of the operating point on the magnetization curve. In the system studied, speed regulation is obtained by means of a slipping magnetic particle clutch which is operated with a feedback loop from the generator terminals. If the terminal voltage is too low, the speed regulator does not function properly, and this puts another limitation on the choice of operating conditions.

The magnetic particle clutch used in this unit is definitely critical with respect to generator terminal voltage. The critical range on starting is from a generator field current of 0.77 amps to 0.89 amps, which corresponds to a terminal voltage range from 77 volts to 86 volts. This is due to the feedback loop, to the speed regulator, which controls the excitation for the magnetic particle clutch. For values of generator field current less than 0.77 amps the clutch is not slipping. The generator speed is actually above synchronous speed. However, when the alternator terminal voltage is at 77 volts, the clutch begins to slip. This effect is noted on the magnetization curve by a displacement to the right of the curve.

Thus it is not considered advisable to operate this unit unless the initial terminal voltage is at least 108 volts. The inherent regulation would be sufficient at this initial terminal voltage to ensure being abov e the critical region at full load.

One other characteristic to be observed is the hysteretic effect

which is noticeable from increasing field current to decreasing field current. In short, the terminal voltage lags the field current when the field current is decreased. Thus for the same value of field current, the terminal voltage will be lower on increasing field current than on decreasing field current.

Lastly the operating region on the magnetization curve can definitely be considered linear.

Figure 23 shows the normal regulation characteristic of the synchronous alternator. To determine the deviation from the desired 120 volts ac the synchronous alternator was loaded and the following three conditions imposed:

(a) All three loadings were conducted the same way, using the same load banks.

(b) The first run was with the voltage regulator in automatic control.

(c) The second run was with the voltage regulator in manual control initially set at 120 volts ac. No further adjustment was made. However, it is to be noted that the synchronous alternator terminal voltage can be manually adjusted to maintain the 120 volts.

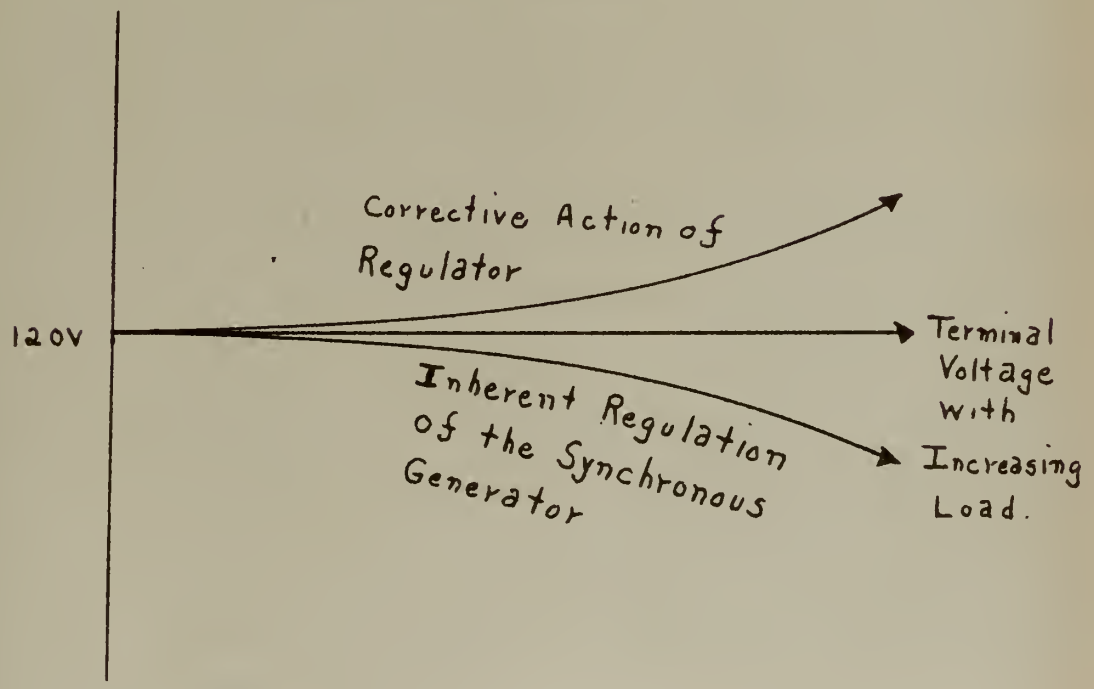
(d) The third run was with no voltage regulation.

This data is shown in figure 23 . The most striking feature is indicated in this graph. In automatic operation the terminal voltage was constant to 130% of full load current. In manual operation the voltage drop was only 8 volts. With no regulation employed, the voltage drop to 130 % of full load current was 36 volts.

The following table summarizes the results of this graph:

	Automatic Operation Voltage Regulator	Manual Operation Voltage Regulator	Operation With No Voltage Regulation
Per Cent Regulation at:			
Full Load	0	4.35	17.65
130% Full Load	1.69	7.15	39.6

The following sketch shows exactly what the voltage regulator must do in order to maintain the terminal voltage.



In order to have a continuity of analysis for this system, the various components will be analyzed as they appear in the voltage loop and current loop as described in figure 20A. Consider first the voltage loop.

The Detector Transformer T1-C7C61-2 is considered to be a linear device over the range of normal operation. This is shown graphically in figure 24 .

The tripler Reactor L1-38B55-2 exhibits definitely a non-linear characteristic as indicated in figure 25 . In effect considering either the output voltage or the output current with respect to the input voltage the hysteretic effect is most pronounced. The output voltage is the main consideration. As a first approximation it is considered valid to derive a best linear expression relating the input and the output voltage.

The rectifier RECT 1-44B30-2 characteristics are shown in figure 26. In this component it is the output current with which we are basically concerned. Whereas the curve of input voltage versus output current deviates slightly from the desired linear characteristic, this amount of deviation is not considered excessive. Therefore we can write a best linear expression for this curve. This fact is further substantiated in figure 27 which shows the relationship between input current and output current and voltage.

The Bias Rectifier 2-44-C79-2 characteristics shown in figure 28 indicate that the output characteristics of voltage and current have non linear properties. Nonetheless it is only fair to point out that the scale of current is in milliamperes and the total voltage deviation is

only one volt. Therefore an equally good linear curve could be drawn to express the relationship. In Appendix II the transfer function of a full wave rectifier was derived. It indicated a rectifier could be expressed in linear terms. Hence as a first approximation this component can be considered a linear device.

The Preamplifier Stage 35C63-2 will be considered as a single unit composed of four variables as indicated in figure 29. This graph could well be considered as a Transfer Characteristic Curve. The salient considerations are:

(a) The Bias Current is definitely a linear variation with load.

(b) The Preamplifier Main Power Current is a linear variation with load.

(c) The Preamplifier Control Current is not an overall linear function, but can be so considered when the scale of control current is noted. The deviation between the non-linear curve and the linear curve are academic points of interest solely in this investigation.

(d) The Preamplifier Output Current is plotted to a different scale than the Input Current however, the similarity between the general contour of each curve is most striking. In short the Output Current will be considered as a linear function for the reasons stated in section (c) above.

A general observation would be that the Preamplifier is operating basically as a gain unit.

Now consider the current loop. TheCurrent Transformer 27C68-2 Characteristics are shown in figure 30 . The voltage and current

characteristics are definitely non-linear and will require a complex expression to describe its transfer function accurately. The derivation of the general transformer transfer function is given in Appendix II but must be specifically applied to this transformer before a workable expression is known. It is felt that this component is primarily responsible for one of the roots in the generalized transfer function given in section (a) of Chapter VI.

The Main Power Rectifier 44C20-2 characteristics shown in figure 31 are a linear function. Both the voltage and the current can be considered as linear functions although the main interest is in the current relationship. Figure 32 shows more effectively the output current of the rectifier.

As for the Preamplifier Stage a Transfer Characteristic Curve for the Final Stage Amplifier was drawn as indicated in figure 38 .

(a) The Preamplifier Control Current and the Final Stage Control Current have the same general type of linear curve.

(b) The Bias Current is a linear function.

(c) The Main Power Current is not a linear function. It will have a general expression similar to the secondary transformer current because the secondary voltage of the current Transformer was applied to the Rectifier 44C20-2 which might be considered as a fractional gain device.

(d) The Output Current is not a linear function but is rather a non-linear function. As might be foreseen there is a marked similarity between the main power current and the generator field current which is the final stage output current.

To bring into clearer focus the importance of the various functions which comprise the final stage, the following graphs were constructed.

(1) The Main Power Final Stage Amplifier Current versus the Generator Field Current and Generator Field Voltage shown in figure 33 shows conclusively the linear relationship which exists.

(2) The Main Power Final Amplifier Stage Voltage versus the Generator Field Current and the Generator Field Voltage shown in figure 34 shows conclusively the linear relationship which exists.

(3) The Final Stage Control Current versus the Generator Field Current and the Generator Field Voltage shown in figure 36 once again point out the definite linear relationship which exists.

(4) The Final Stage Control Voltage versus the Generator Field Current and the Generator Field Voltage shown in figure 35 approximates closely the linear characteristics.

These four graphs indicate the very definite desirable linear characteristic of the final stage amplifier when only the input currents are the references with respect to the generator field current and the generator field voltage. However, when we take the generator output current as the reference the non-linearity characteristic prevails. As the transfer function of the final stage amplifier is the component being considered and it is assumed that there is negligible interaction, the input current references are valid.

As it is the generator field current which is the main consider-

ation, figure 37 shows the generator line current versus the generator field current and the generator field voltage. These curves definitely emphasize the non-linear characteristic of the generator field current and the generator line current. This is easily confirmed theoretically when we recall the region of operation on the magnetization curve, which was assumed to be linear but in fact was somewhat non-linear.

The Generator Terminal Voltage, the Generator Field Voltage, the Control Voltage Preamplifier Stage, the Control Voltage Final Amplifier Stage, and the Bias Voltage were plotted versus load current as indicated in figure 39 with the voltage regulator operating in automatic. All voltages were constant through 140% full load current except the generator field voltage which increased from a fixed value with the application of load.

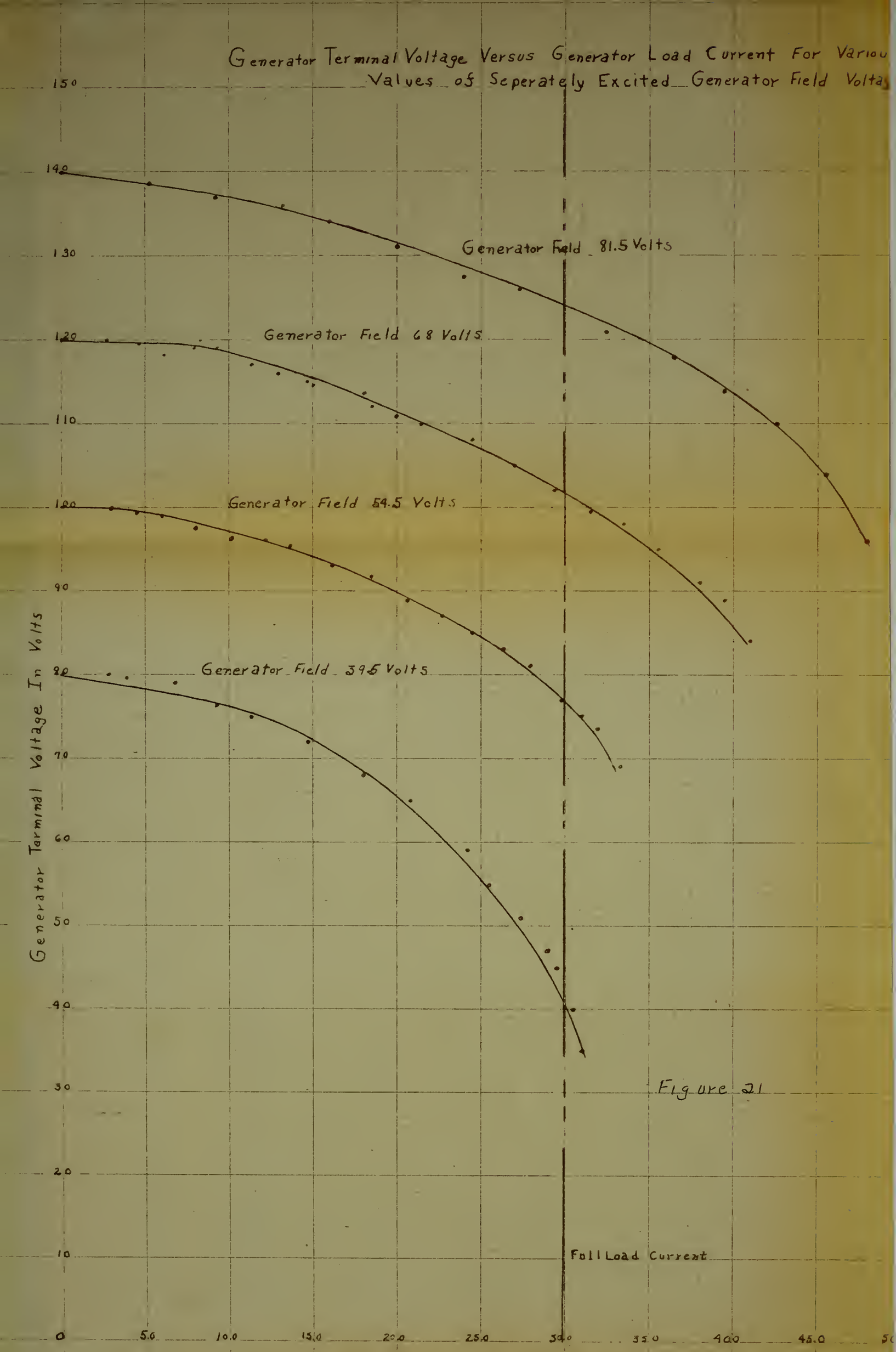

Generator Terminal Voltage Versus Generator Load Current For Various Values of Seperately Excited Generator Field Voltage
Generator Field 81.5 Volts
Generator Field 68 Volts
Generator Field 54.5 Volts
Generator Field 39.5 Volts
Full Load Current
Generator Terminal Voltage In Volts
Generator Load Current In Amperes
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0

Figure 21

Magnetization Curve

Generator 180

Terminal Voltage In Volts

160
140
120
100
80
60
40
20
0

Normal Range of Field Current From No Load To Full Load

122 146

Speed Above Critical Range Constant at Synchronous Speed 3428 RPM

Up To Critical Range Speed Constant at 3650 RPM

Critical Range For Magnetic Particle Clutch When Starting

Legend: ○○○ Increasing Values of Field Current

△△△ Decreasing Values of Field Current

△ ← Generator Terminal Voltage Drops Off Radically and Speed Decreases

0.0 .20 .40 .60 .80 1.00 1.20 1.40 1.60 1.80 2.00 2.20

Field Current In Amperes

Figure 22

Generator Terminal Voltage Versus Load Current For
(1) Automatic Voltage Regulation △△△
(2) Manual Voltage Regulation ○○○
(3) No Regulation □□□

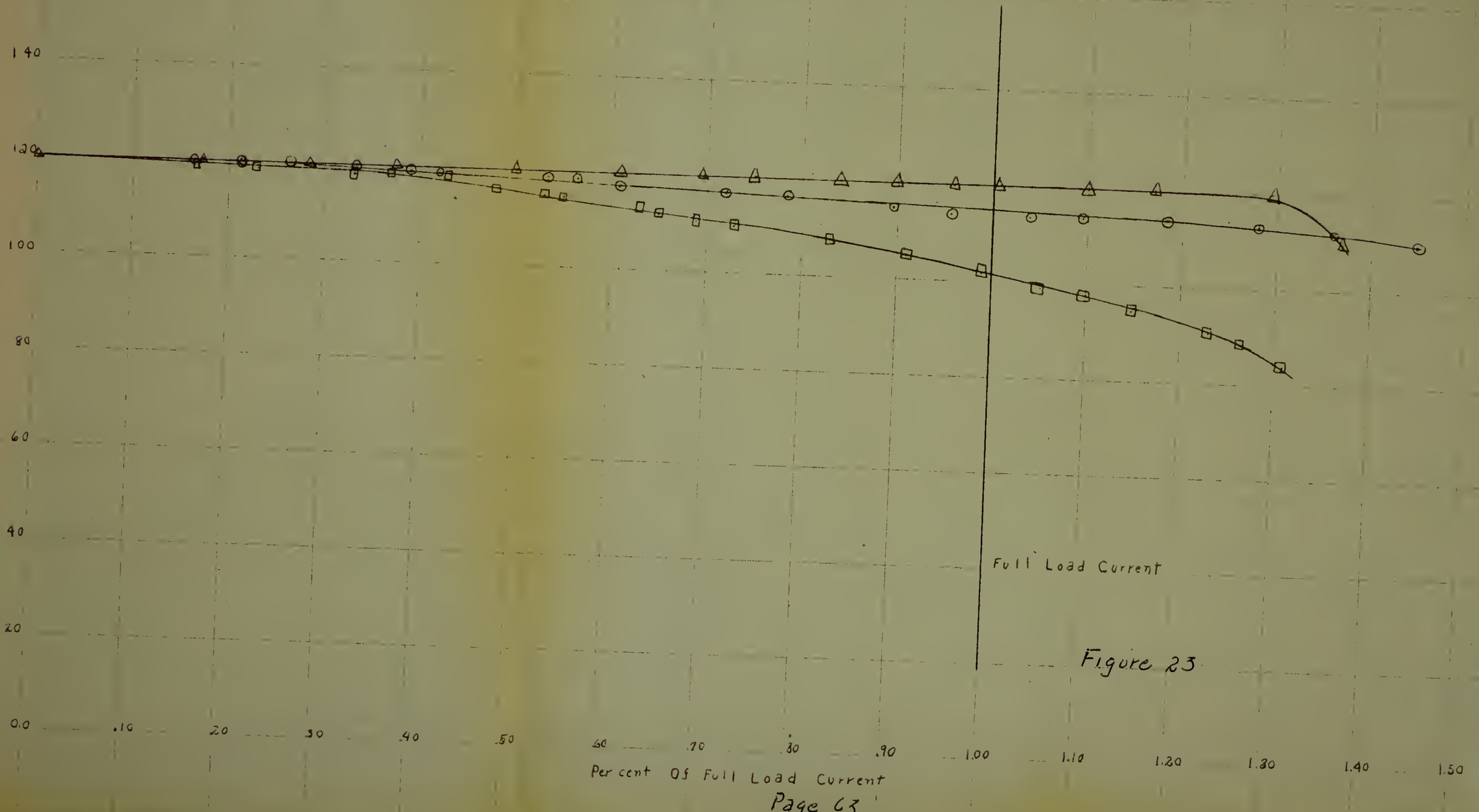


Figure 23

Primary Voltage Versus Secondary Voltage

of Transformer T1-27C61-2

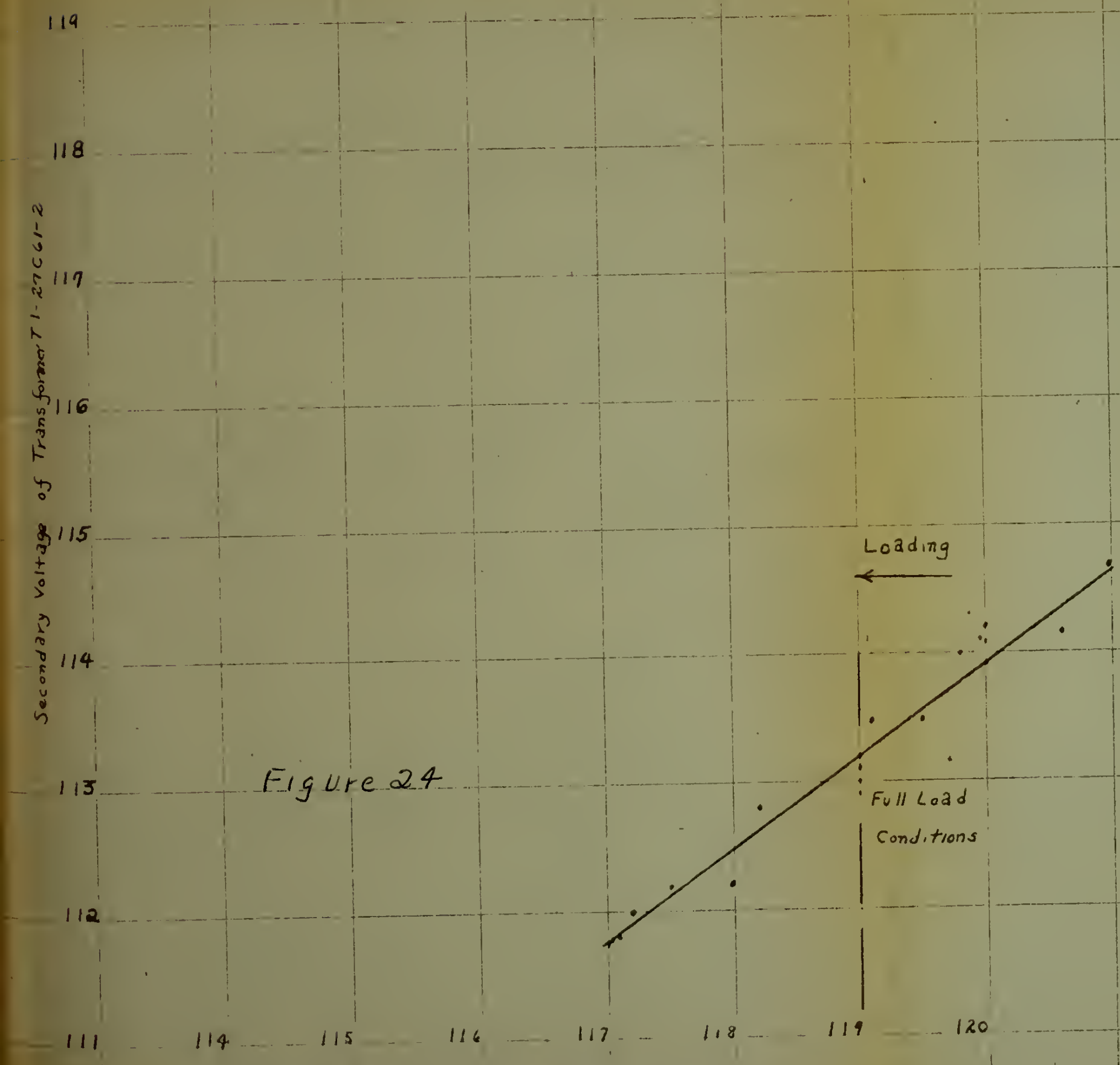


Figure 24

Tripler Input Voltage Versus Output Voltage and Current

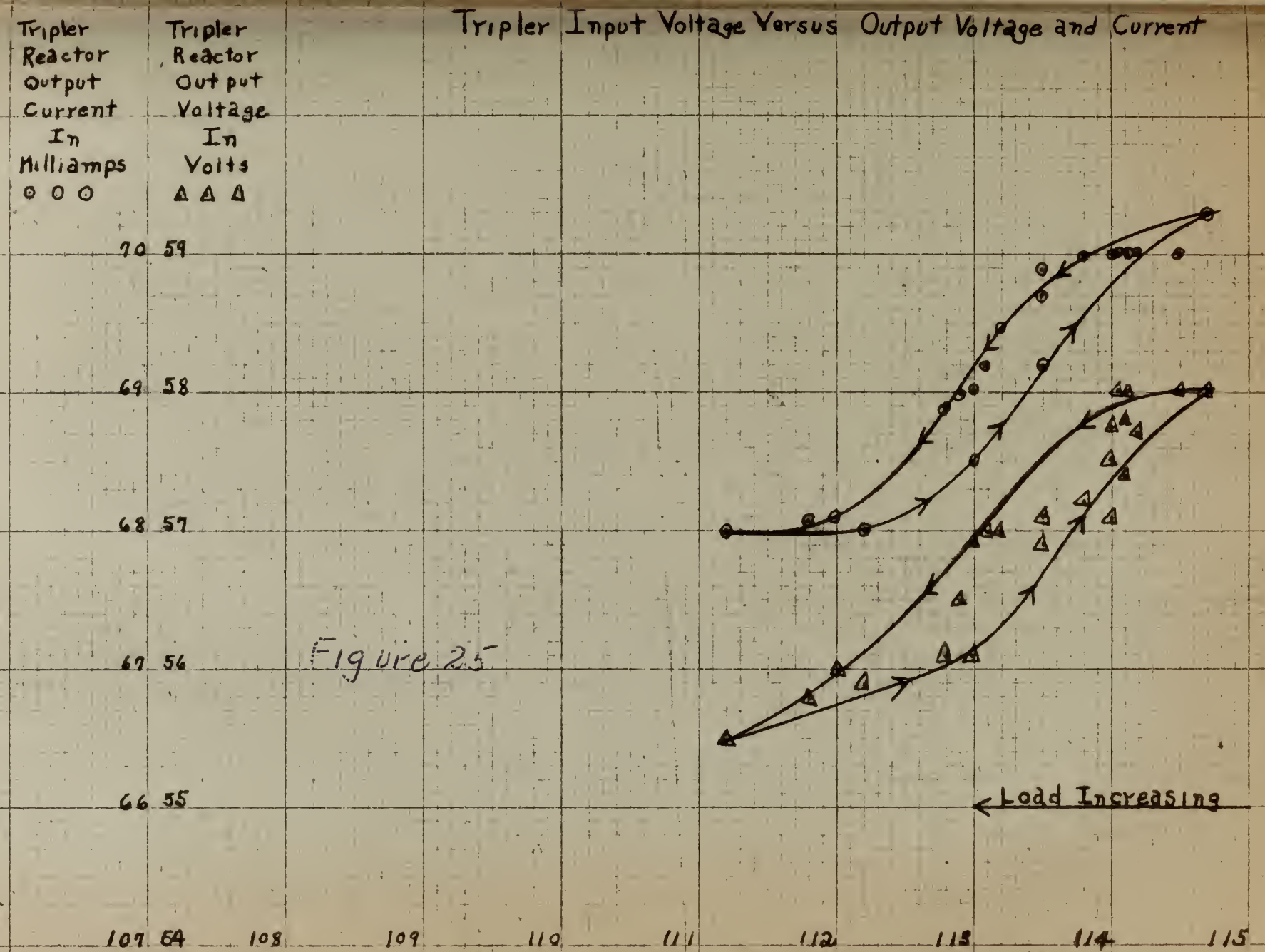


Figure 25

Input Voltage To Tripler Reactor 38B55-2-L1

As a Function of Input Volts

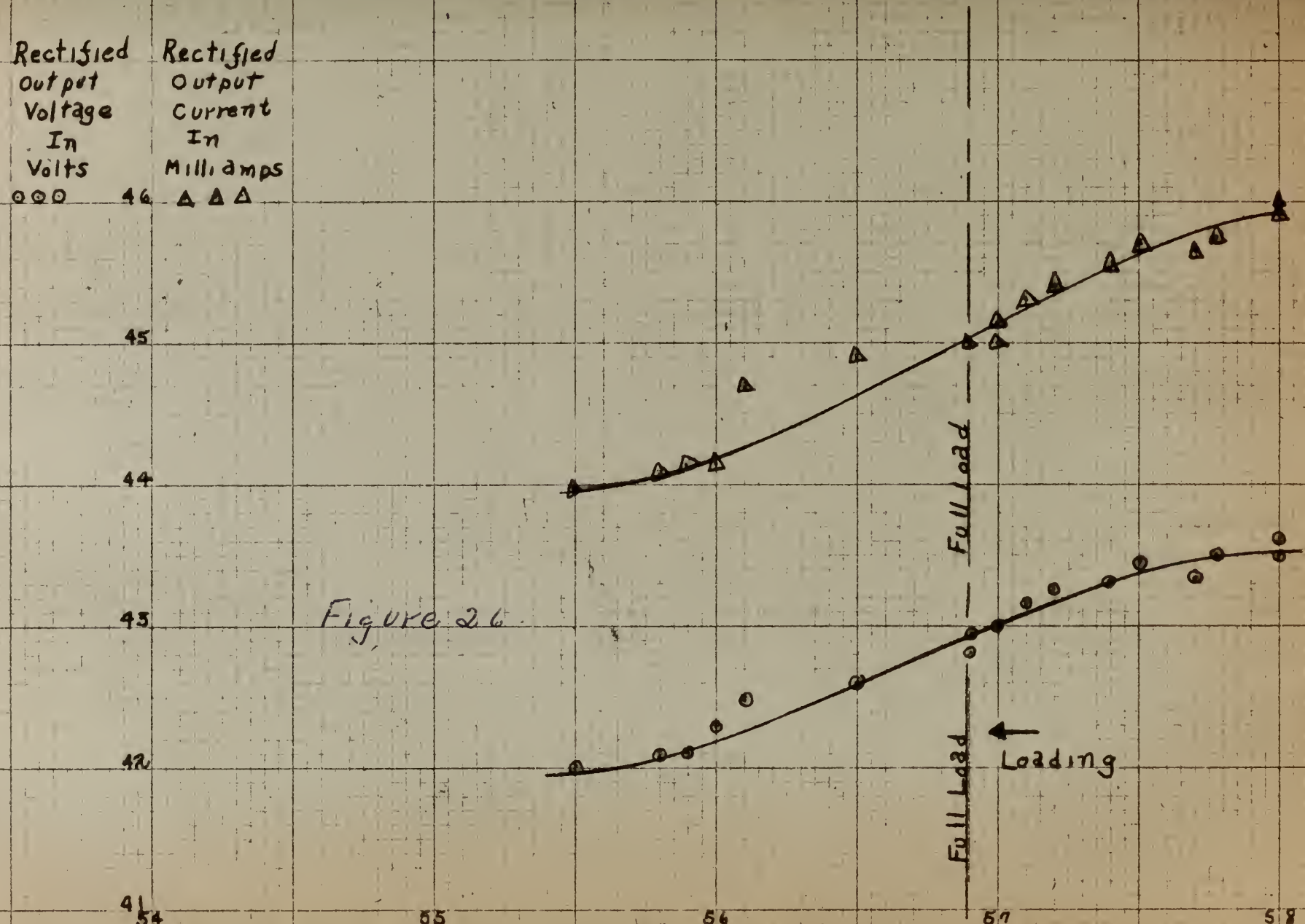


Figure 26.

Rectifier 1-44B30-2 Output Voltage and Current Characteristics

As A Function of Input Current

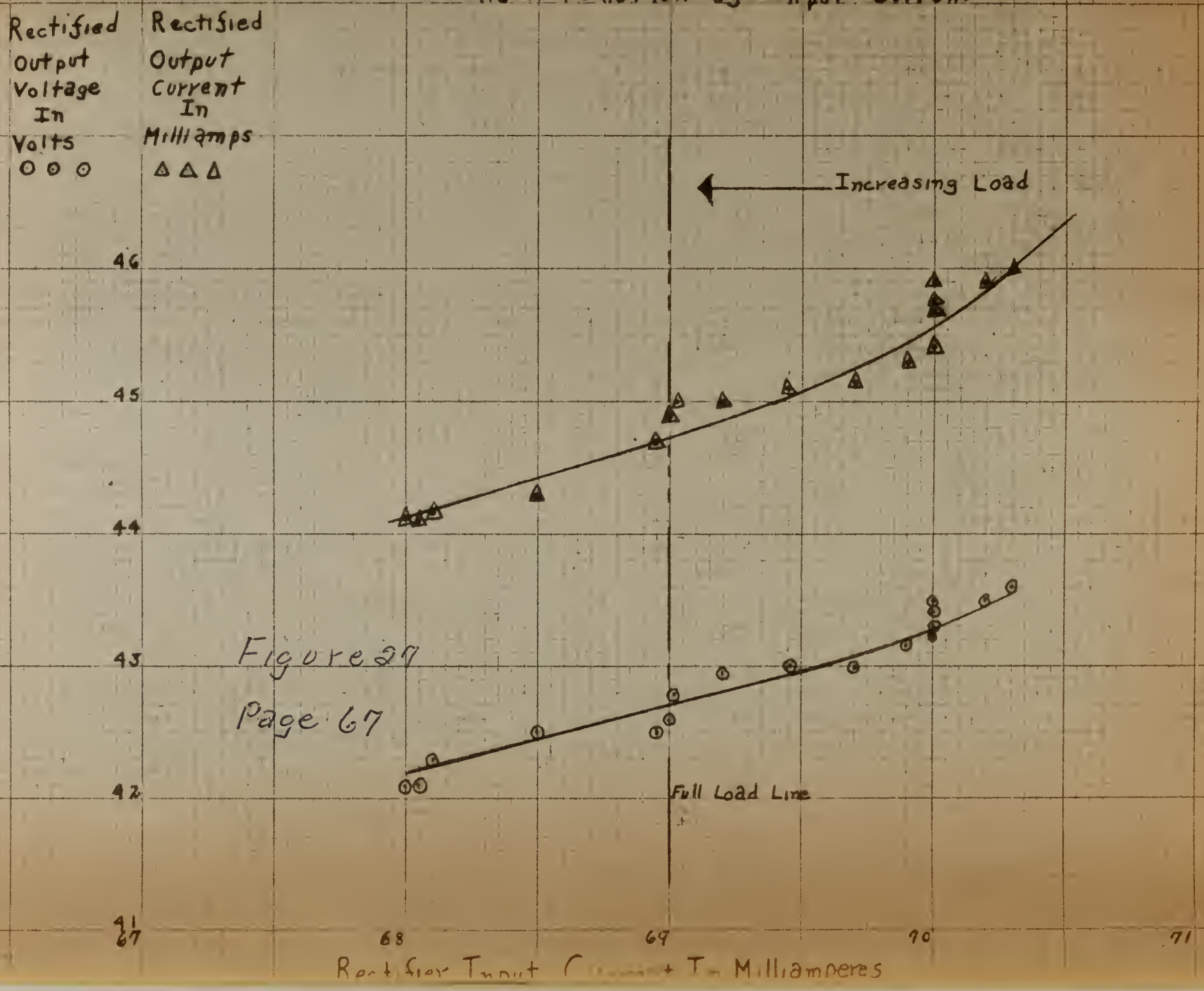


Figure 29

Page 67

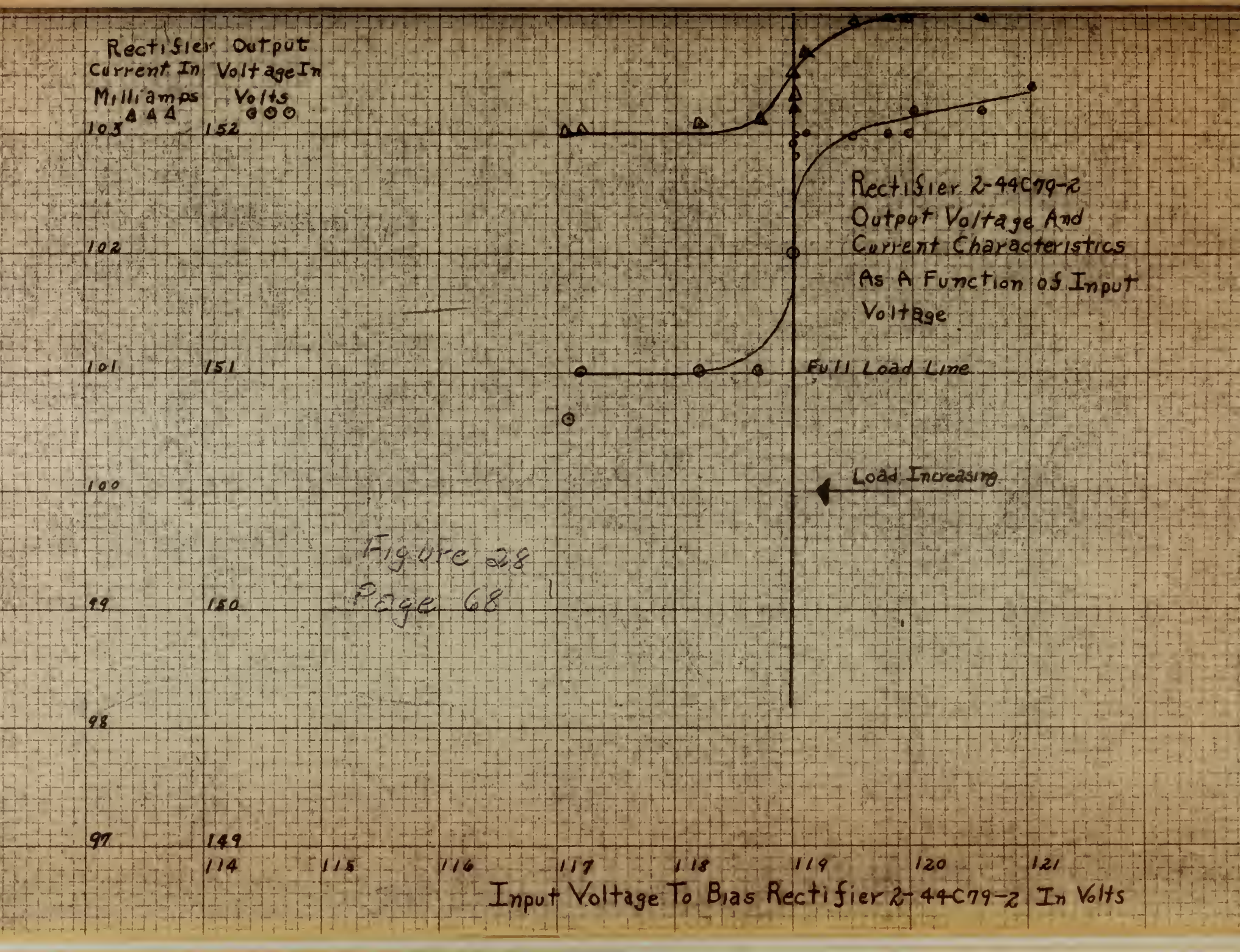


Figure 28
Page 68

Preamplifier Control Current In Milliamps ○○○

Preamplifier Main Power Current In Milliamps □□□

Preamplifier Output Current In Milliamps △△△

Preamplifier Bias Current In Milliamps • • • ○

Generator Load Current Versus (1) Preamplifier Control Current (2) Preamplifier Main Power Current (3) Preamplifier Output Current (4) Preamplifier Bias Current

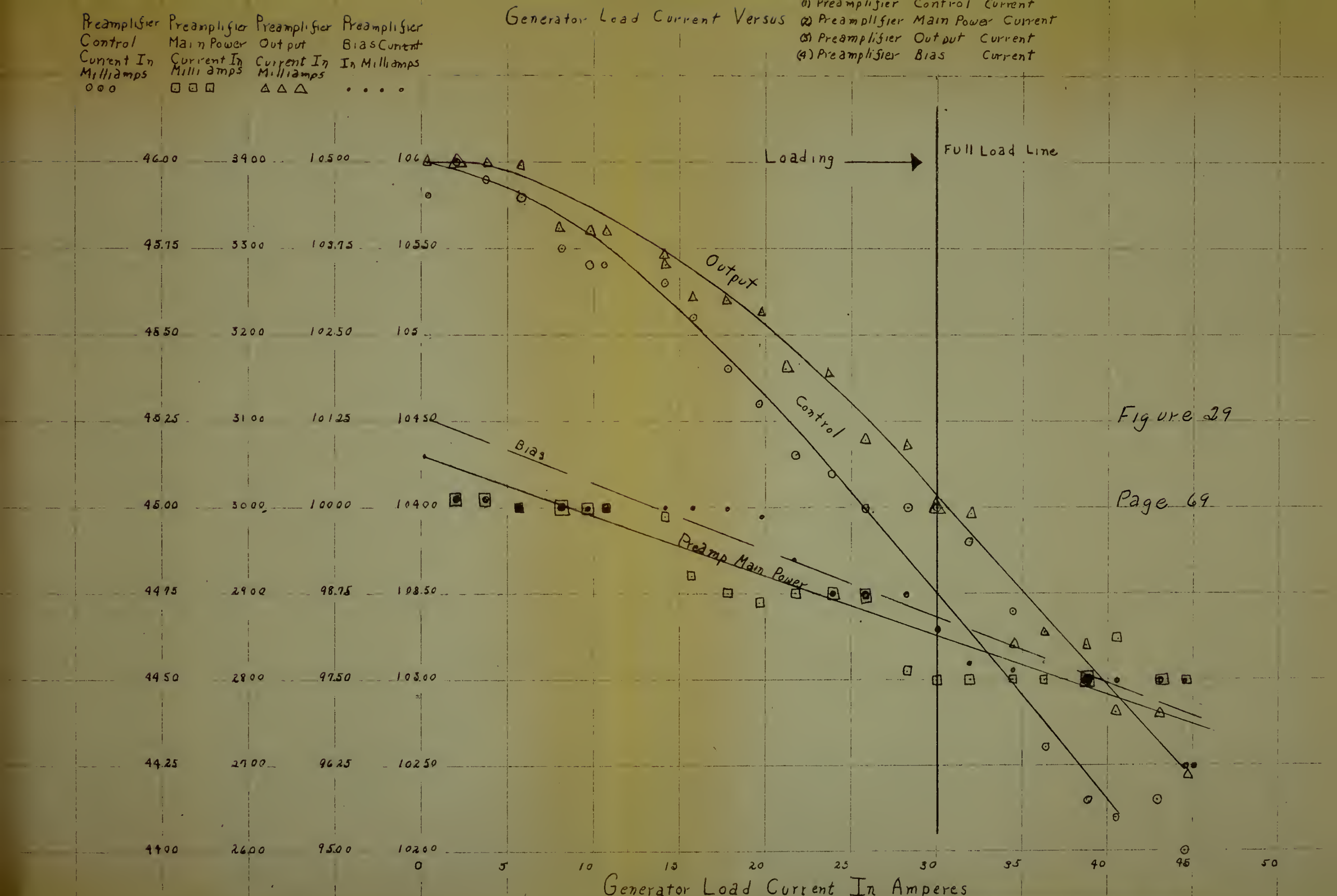
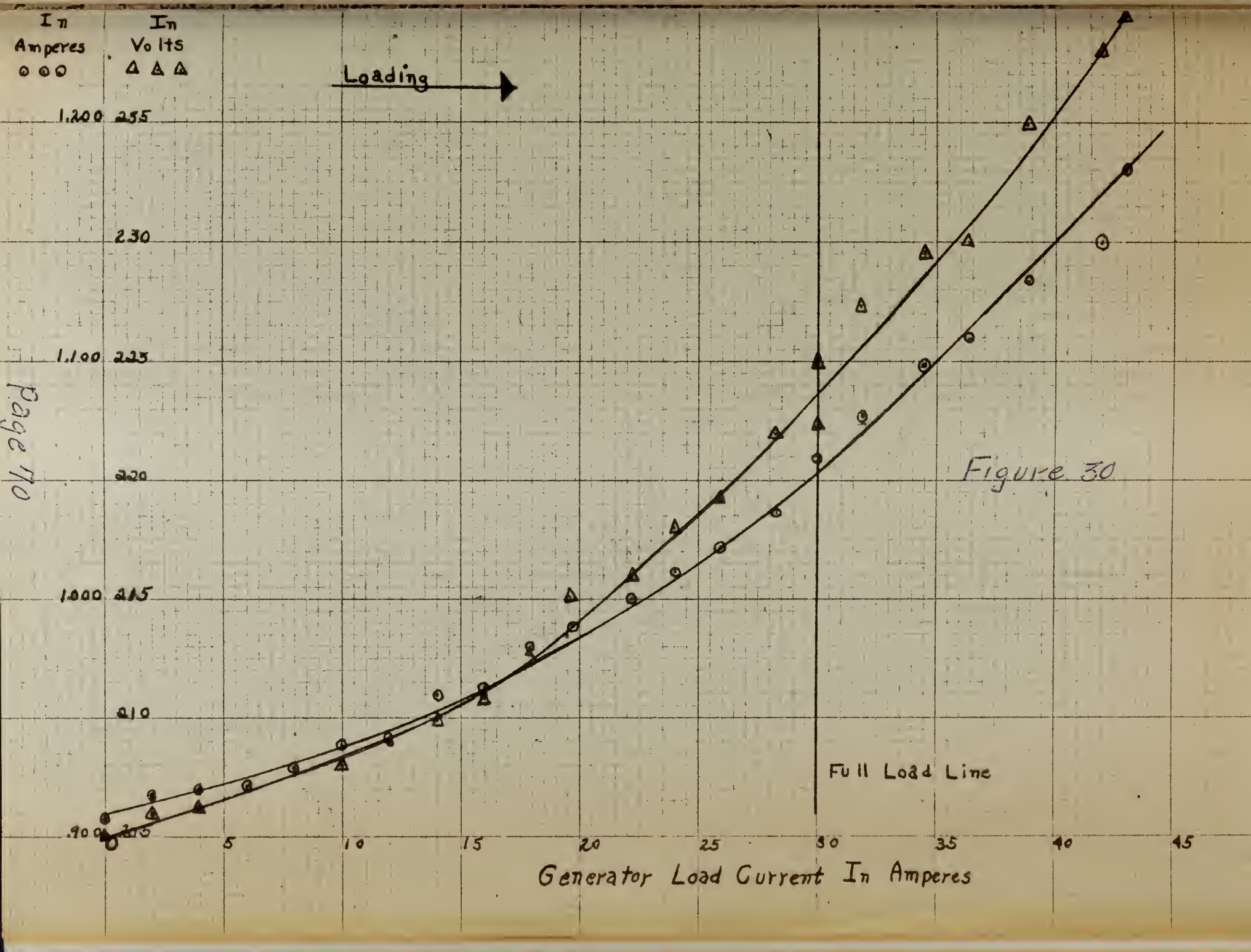


Figure 29



Page 110

Figure 30

Main Power Rectifier 44C20-2 Final Stage Input Voltage Versus Output Current and Voltage

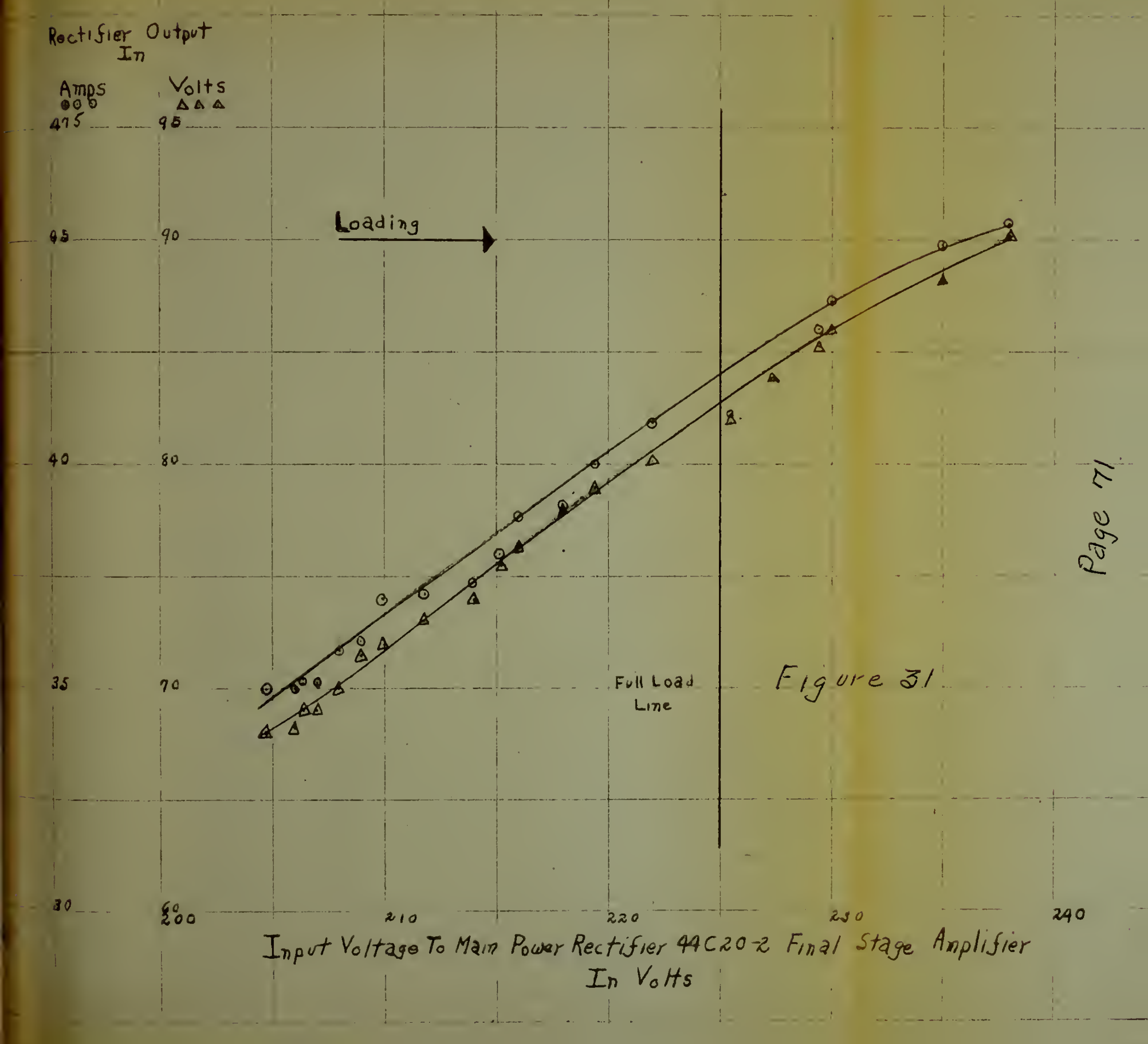


Figure 31

Main Power Rectifier 44C20-2 Final Stage Amplifier Input Current Versus Output Current and Voltage

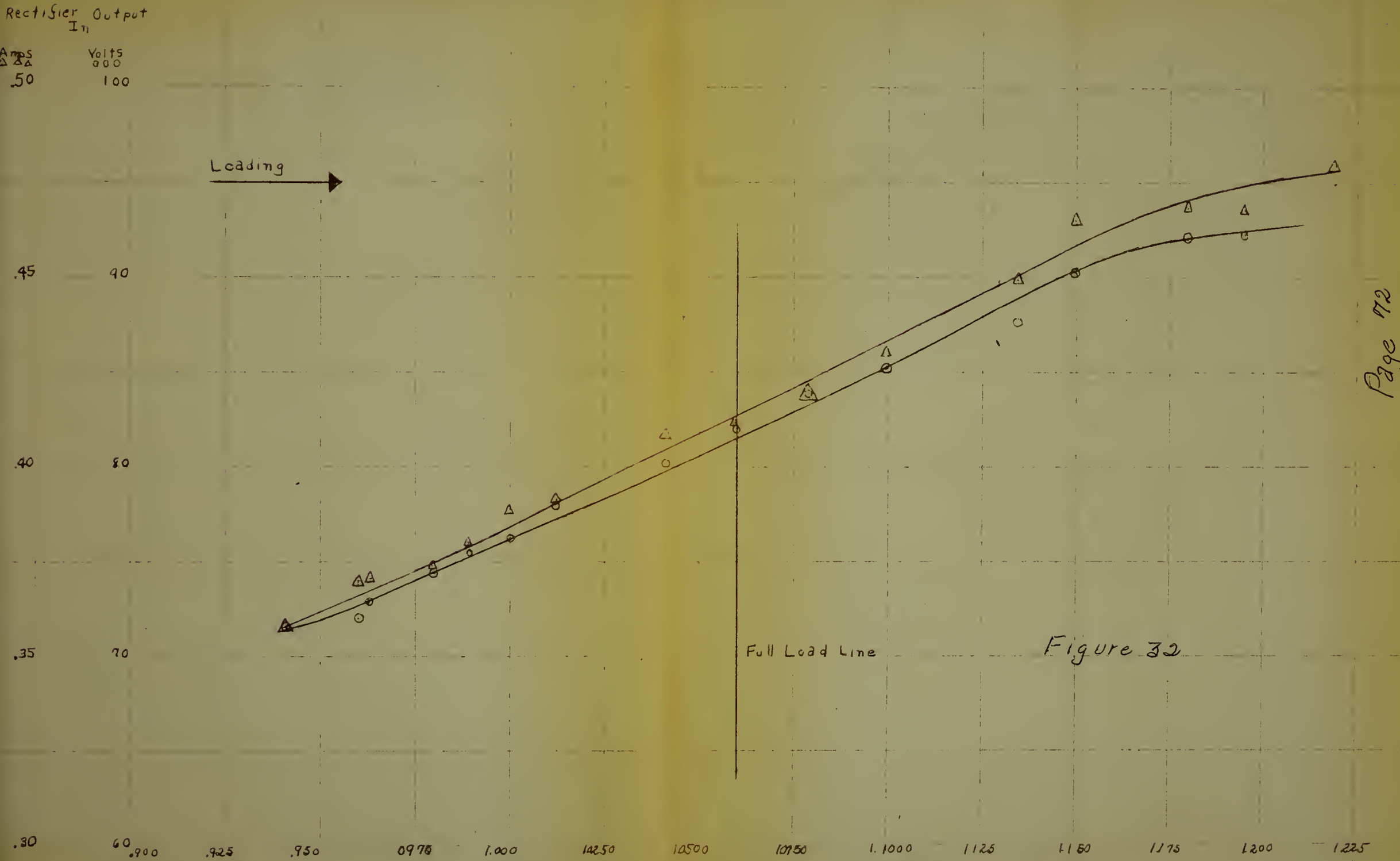


Figure 32

Input Current To Main Power Rectifier 44C20-2 Final Stage Amplifier In Amperes

Main Power Final Amplifier Stage Current Versus Generator Field Current And Voltage

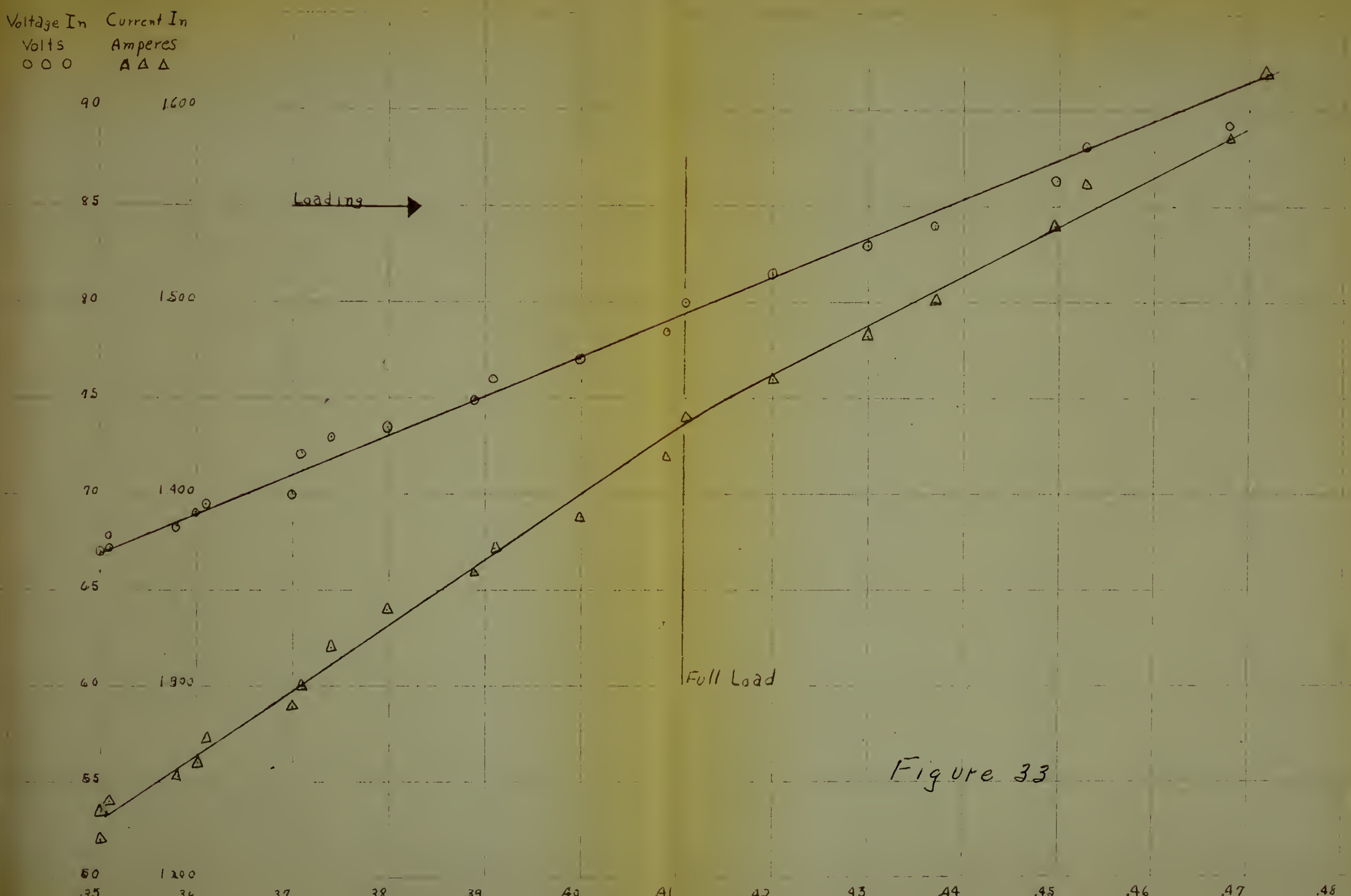


Figure 33

Main Power Final Amplifier Stage Voltage Versus Generator Field Current And Voltage

Generator Field Voltage In Volts	Generator Field Current In Amperes

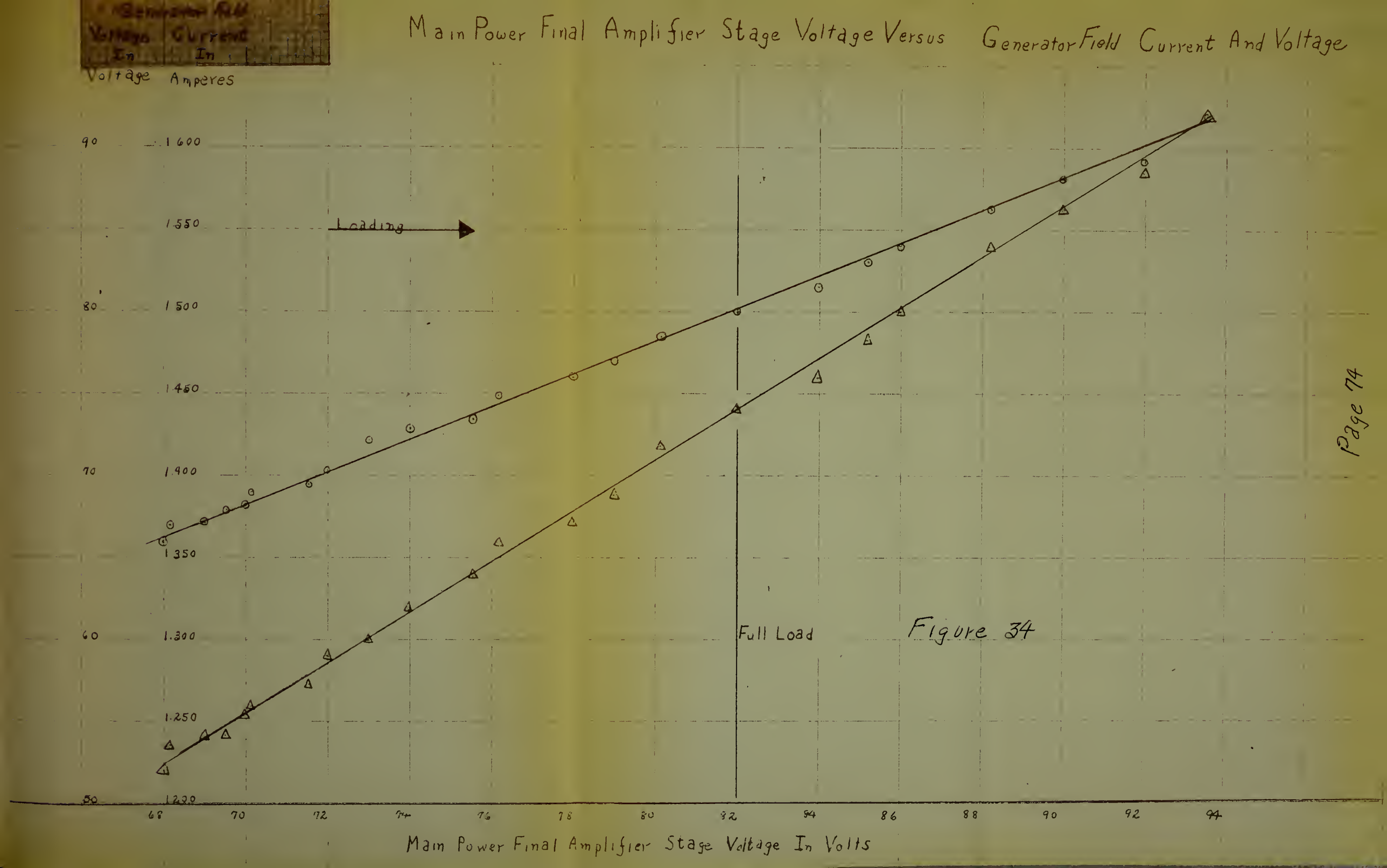


Figure 34

Final Stage Amplifier Control Voltage Versus Generator Field Current And Voltage

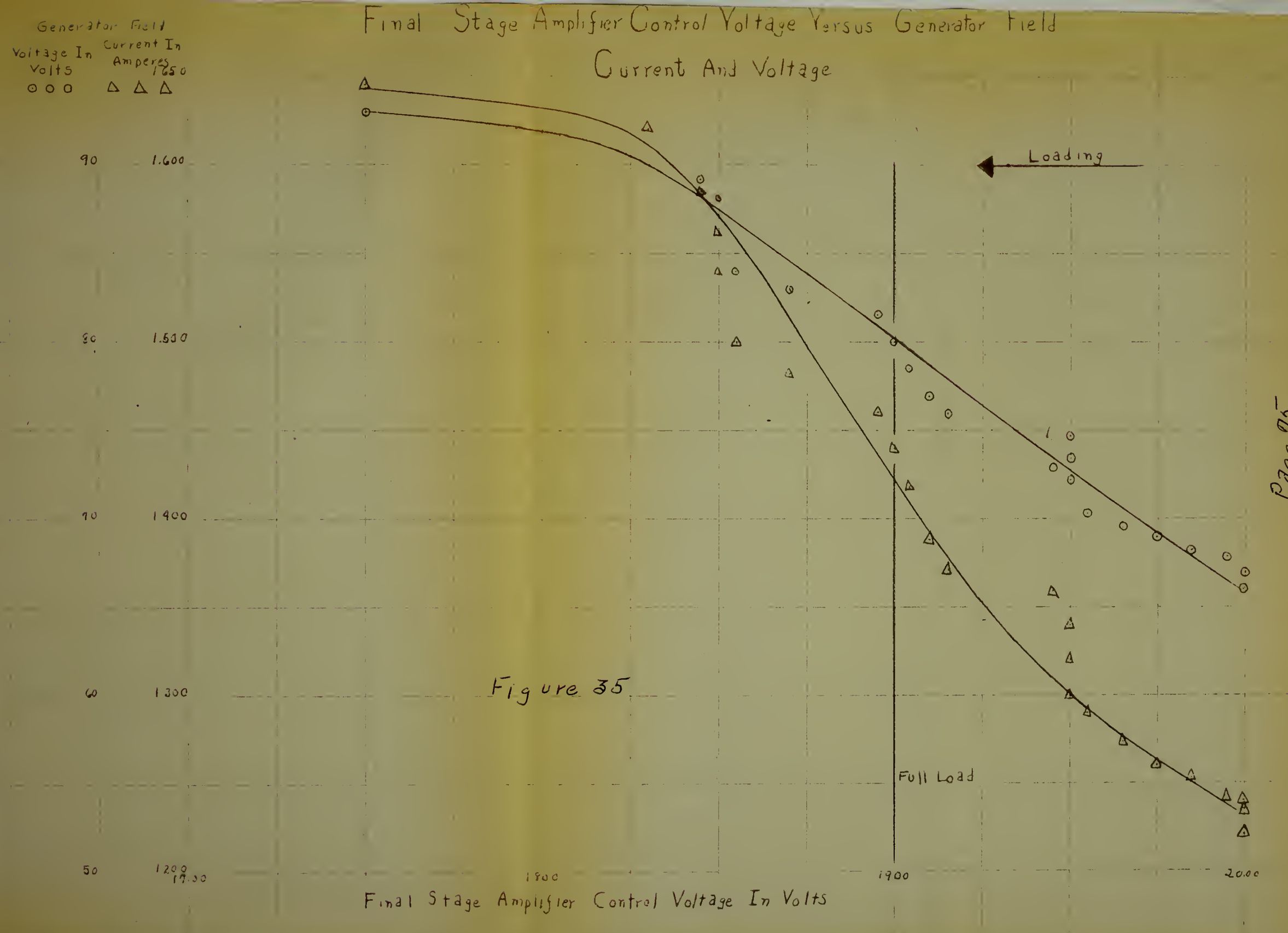


Figure 35

Final Stage Amplifier Control Current Versus Generator Field Current And Voltage

Generator Field Voltage In Volts ⊙ ⊙ | Current In Amperes △ △

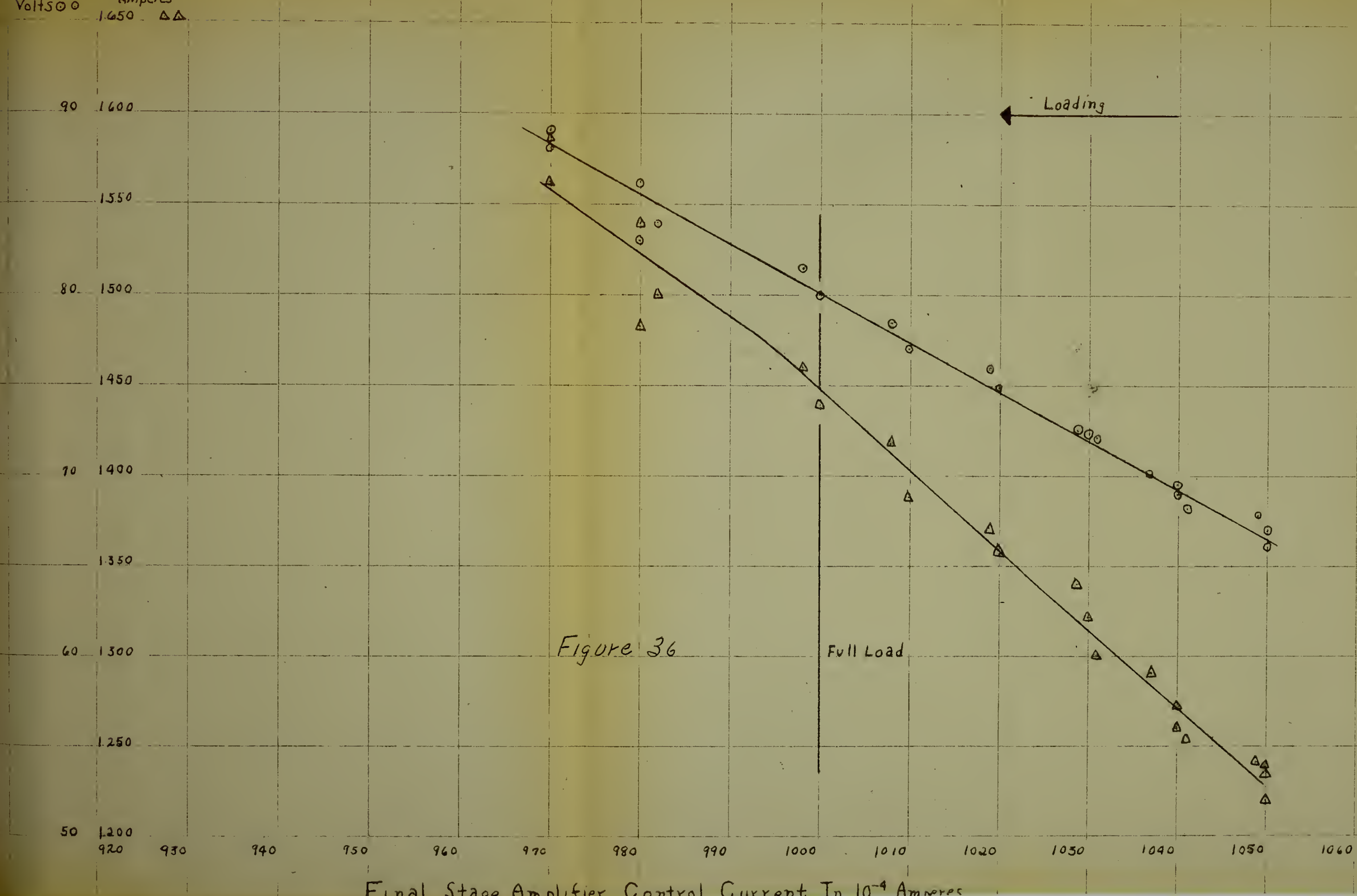


Figure 36

Final Stage Amplifier Control Current In 10^{-4} Amperes

Generator Field Current In Amperes △ △ △

Generator Field Voltage ○ ○ ○

Generator Line Current Versus Generator Field Current and Generator Field Voltage

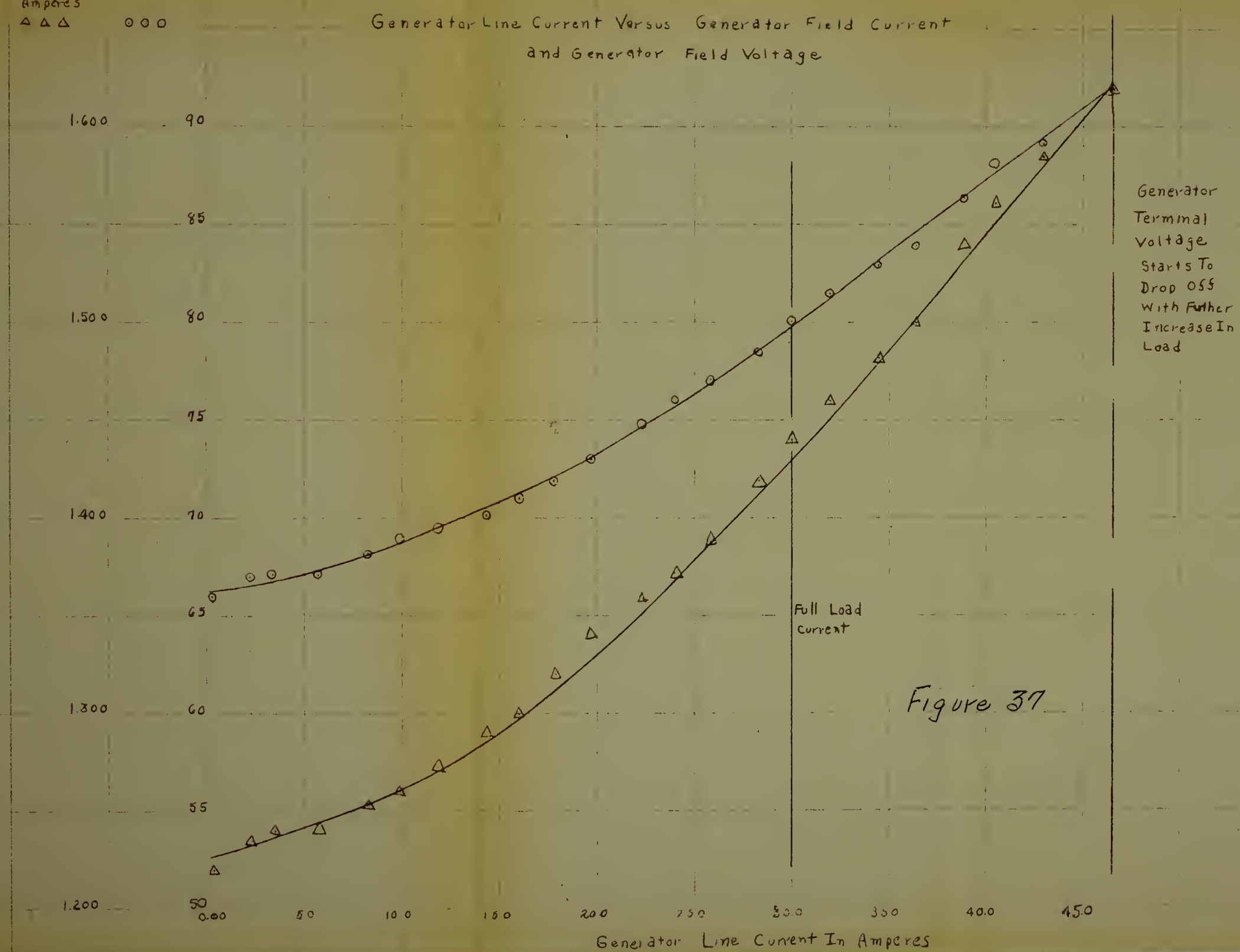


Figure 37

Generator Load Current Versus

(1) Preamplifier Stage Control Current
(2) Final Stage Control Current
(3) Final Stage Main Power Current
(4) Final Stage Output Current
(5) Final Stage Bias Current

Preamplifier Control Current In Milliamps ○ ○ ○	Final Stage Control Current In Milliamps □ ⊡ ⊡	Final Stage Main Power Current In Milliamps ◊ ◊ ◊	Final Stage Output Current In Amperes • • •	Final Stage Bias Current In Milliamps △ △ △
			1.600	
			1550	
460		500	1500	
455.	1075.	475	1450	
450	1050	450	1400	
445	1025	425	1350	139
440	1000	400	1.300	138
435	975	375	1.250	137
430	950	350	1.200	136

0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0

Generator Load Current In Amperes

Figure 38

Page 78

Load Current Versus

(1) Generator Terminal Voltage
(2) Generator Field Voltage
(3) Control Voltage Final Amplifier Stage
(4) Control Voltage Preamplifier Stage
(5) Bias Voltage

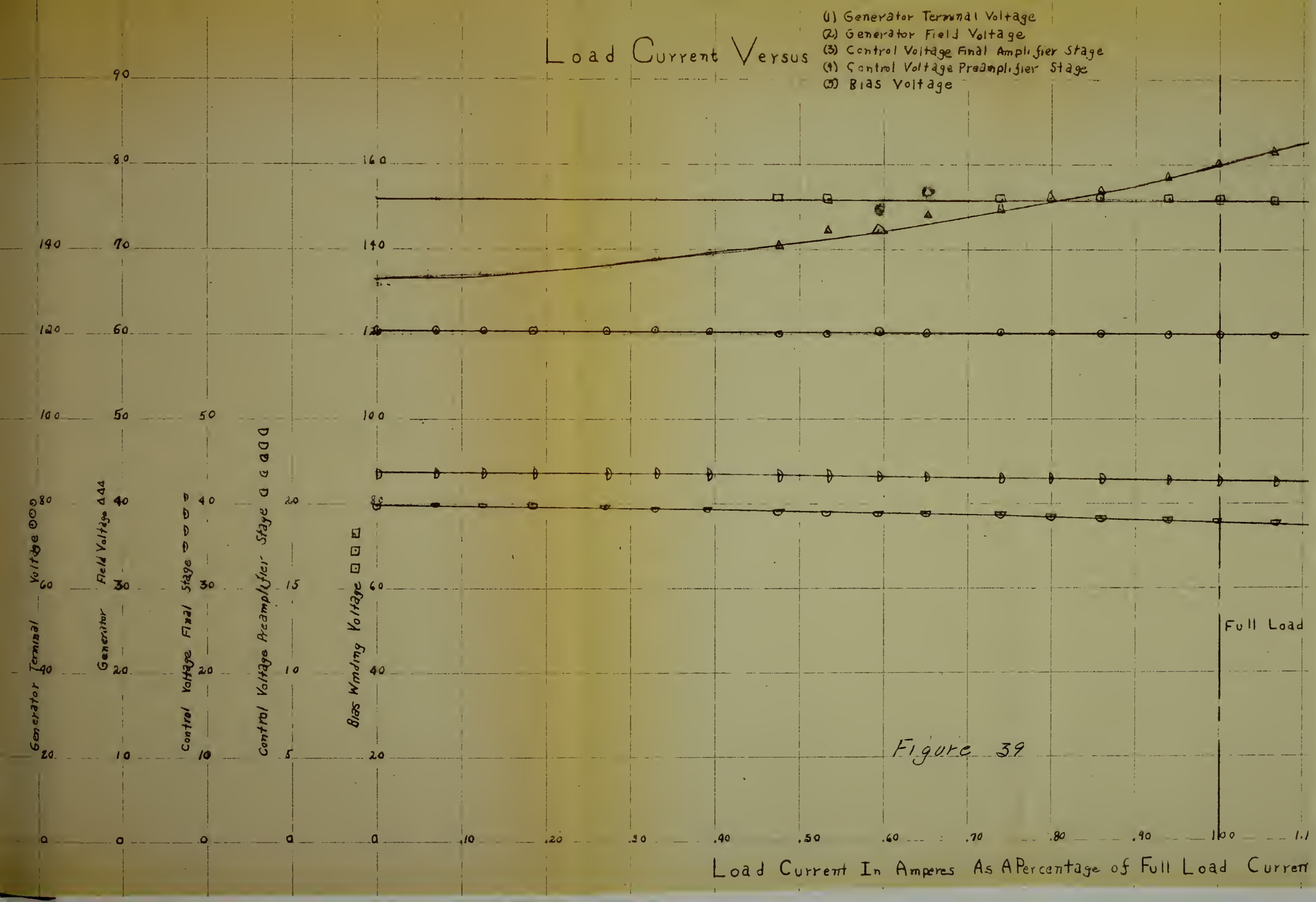


Figure 39

(C) The Significance of the Transient Data.

The transient analysis of the system was conducted as stated in Chapter IV to determine the effect of the stepped loading on the various functions. The graphical results are shown in figures 40 through figure 50 .

The following definitions were used in analyzing the transient curves.

Mp': The ratio between the magnitude of the maximum excursion from the initial steady state value to the difference between the two steady state values.

Rise Time:

It is the time from the application of the step function until the maximum excursion from the initial steady state value.

Settling Time:

It is the time from the application of the step function until the curve comes within and stays within a plus or minus 2% band of the final steady state value.

For the Magnetic Particle clutch the conventional definition is used for Mp' rather than that previously stated here. The Dead Time for the Magnetic Particle Clutch is that time during which the excitation for the clutch is zero. Thus actually the initial steady state value of the clutch is zero before the clutch becomes excited.

The reference to which the settling time is compared is four hundred cycles.

The following tables summarize the results of the transient loadings.

Preamplifier Control Circuit

No Load To Various Loadings	Mp'	Rise Time In Sec.	Settling Time In Sec. -	In Cycles
26 amperes	18.0	0.008	0.045	18.0
31 amperes	13.4	0.009	0.047	18.8
37 amperes	8.8	0.010	0.060	24.0
Various Loadings to No Load				
26 amperes	18.0	0.002	0.04	16.0
31 amperes	10.1	0.002	0.04	16.0
36 amperes	7.7	0.002	0.04	16.0
Bias Control Circuit:				
No Load To Various Loadings				
26 amperes	6.09	0.007	0.015	6.0
31 amperes	6.26	0.007	0.015	6.0
37 amperes	2.60	0.009	0.018	7.2
Various Loadings to No Load				
26 amperes	4.60	0.016	0.020	8.0
31 amperes	1.84	0.018	0.020	8.0
37 amperes	4.0	0.019	0.019	7.6

Final Stage Amplifier Control Circuit:

No Load To Various Loadings	Mp'	Rise Time In Sec.	Settling Time In Sec. -	In Cycles
26 amperes	44.0	0.006	0.03	12.0
31 amperes	14.4	0.008	0.034	13.6
37 amperes	13.0	0.009	0.042	16.8
Various Loadings to No Load				
26 amperes	8.2	0.005	0.015	6.0
31 amperes	8.34	0.007	0.019	7.6
37 amperes	7.00	0.010	0.020	8.0

Final Stage Amplifier Main Power Circuit:

No Load To Various Loadings				
23 amperes	7.73	0.002	0.04	16.0
30 amperes	6.25	0.002	0.04	16.0
35 amperes	5.65	0.002	0.04	16.0
Various Loadings to No Load				
25 amperes	6.27	0.002	0.04	16.0
30 amperes	6.85	0.002	0.04	16.0
35 amperes	7.50	0.002	0.04	16.0

Generator Field Circuit:

No Load To Various Loadings	Mp'	Rise Time In Sec.	Settling Time In Sec. -	In Cycles
25 amperes	12.0	0.006	0.042	16.8
30 amperes	12.7	0.007	0.040	16.0
35 amperes	8.9	0.005	0.042	16.8
Various Loadings to No Load				
25 amperes	7.1	0.001	0.05	20.0
30 amperes	6.69	0.001	0.05	20.0
35 amperes	4.40	0.002	0.052	20.8

Magnetic Particle Clutch:

Full Load To No Load				
30 amperes	1.160	0.78	1.0	400
No Load To Full Load				
30 amperes	1.136	0.64	1.0	400

Preamplifier Control Circuit:

There is a slight difference in the overshoot values for the loading condition as compared to the unloading condition. The rise time and the settling time increase with application of greater loadings; however, the rise time and the settling time for the unloading condition are the same. There appears to be a greater tendency to oscillate initially for the loading condition but this tendency is reduced exponentially with time as shown in figure 43 .

Bias Control Circuit:

The Mp's for the loading condition do not follow the conventional pattern in that up to full load they increase, but fall off abruptly with further loading. The opposite effect is noted in the unloading condition in that up to full load the Mp' decreases and with further application of load the Mp' increases. There is a markedly different rise time for the increasing load. It is nearly four times longer than the unloading rise time. It must be recognized that for the Bias Control Circuit the Mp' never leaves the two percent band with respect to the final steady state value although the curves in figures 41 and 42 would indicate poor response time. For this circuit only the virtual final steady state was the reference for response time.

Final Stage Amplifier Control Circuit:

The Mp's for the loading condition are surprisingly large when considered with respect to the conventional servomechanism values ranging from 1.2 to 1.6. The Mp's for the loading condition are nearly twice the values for the unloading condition; however, the rise times are comparable. For the higher values of loading the rise time is higher which is also

true for the settling time. It means that though the value of Mp' may be large the response time is quicker than noted in the previous circuits. Thus there is a definite relationship which exists between Mp' and rise time. Lastly the tendency to oscillate with application of load is noted but decreases rapidly exponentially with time.

Final Stage Amplifier Main Power Circuit:

The most striking phenomena to be noted is the same rise time and settling for both the loading and the unloading condition. Such is not the case with the Mp's. For the loading condition, the Mp's decrease with increase of load; however, the opposite condition is true for the unloading condition. The Mp's increase with increasing load. The tendency to oscillate with application of load is noted; however, the rapid exponential decay is very favorable, thus securing desirable and reasonable response time characteristics.

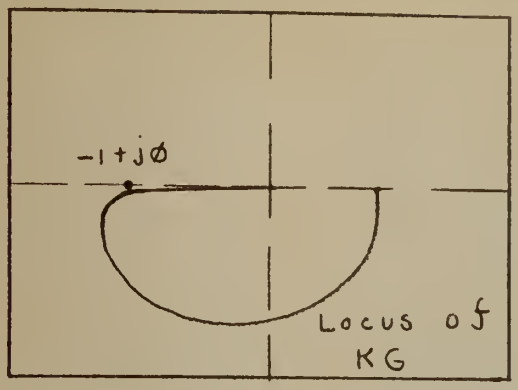
Generator Field Circuit:

The Mp's for the loading condition are nearly twice the unloading condition whereas the rise times are over five times greater. The response time, settling time, is the noteworthy consideration in that final steady state value is realized very quickly. The tendency to oscillate is prevalent, but is damped very quickly as indicated in figures 50 and 49 .

Magnetic Particle Clutch:

The Mp's are reasonable when compared with the standard servomechanism definition. However, the rise time and the settling time are measured from the initial step rather than the second step, thus accounting for the relatively higher values.

The very high values for Mp' is explained on the polar plot basis.



The regulator would be classified as a Type Zero System. Thus the general contour of the locus of K G would be as indicated in the above diagram. The locus is such that it comes very close to the -1 + jØ point, which would account for the high values of Mp'. Secondly the frequency is so high that the transient passes through this point very quickly and stability is maintained.

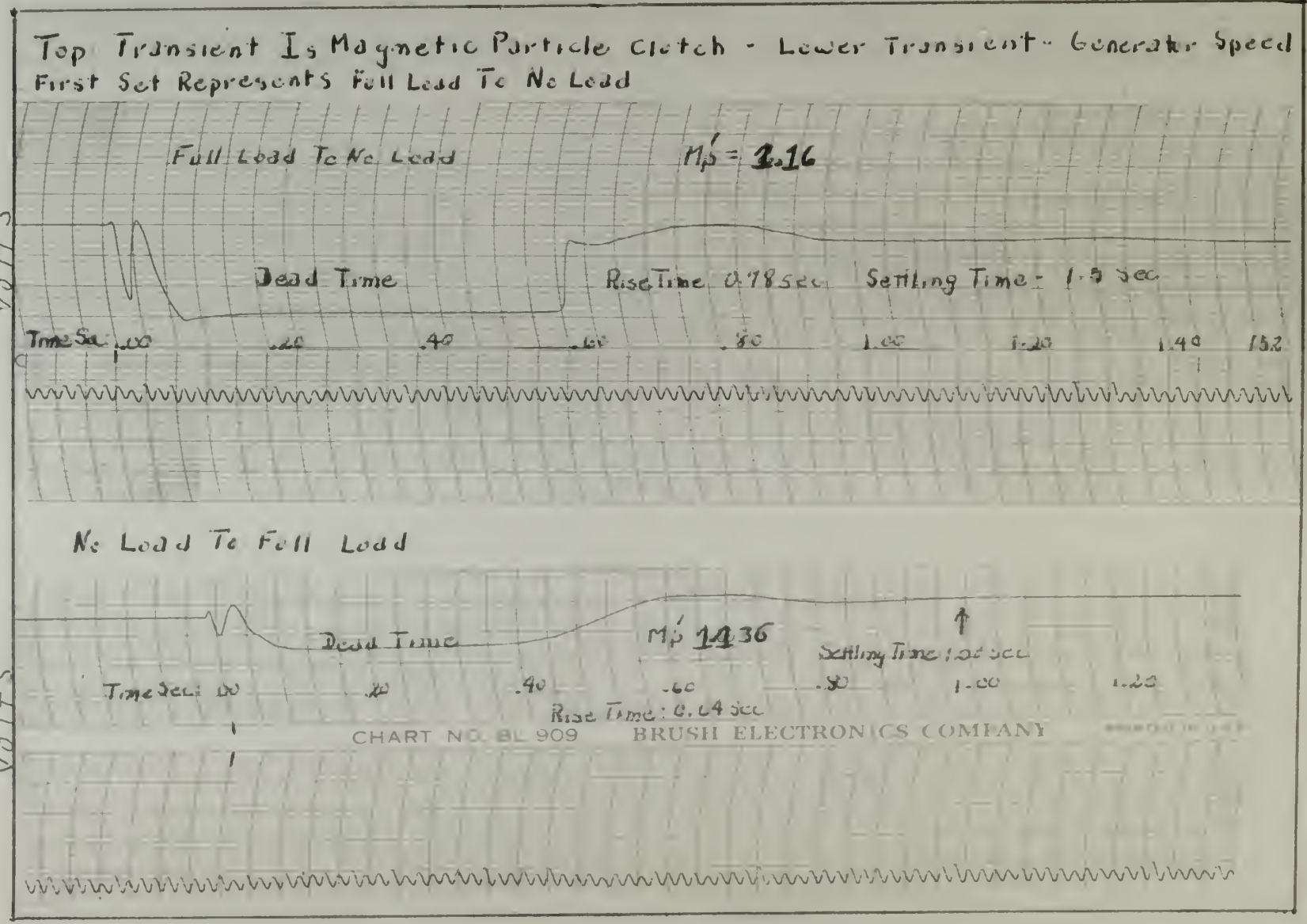

Top Transient Is Magnetic Particle Clutch - Lower Transient - Generator Speed
First Set Represents Full Load To No Load
Full Load To No Load
Mp' = 1.16
Dead Time
Rise Time 0.78 sec
Settling Time - 1.5 sec
Time Sec: .00
.20
.40
.60
.80
1.00
1.20
1.40
1.52
Volts
No Load To Full Load
Dead Time
Mp' 1.36
Settling Time 1.00 sec
Time Sec: .00
.20
.40
.60
.80
1.00
1.20
Rise Time: 0.64 sec
CHART NO. BL 909
BRUSH ELECTRONICS COMPANY
Volts

Figure 40

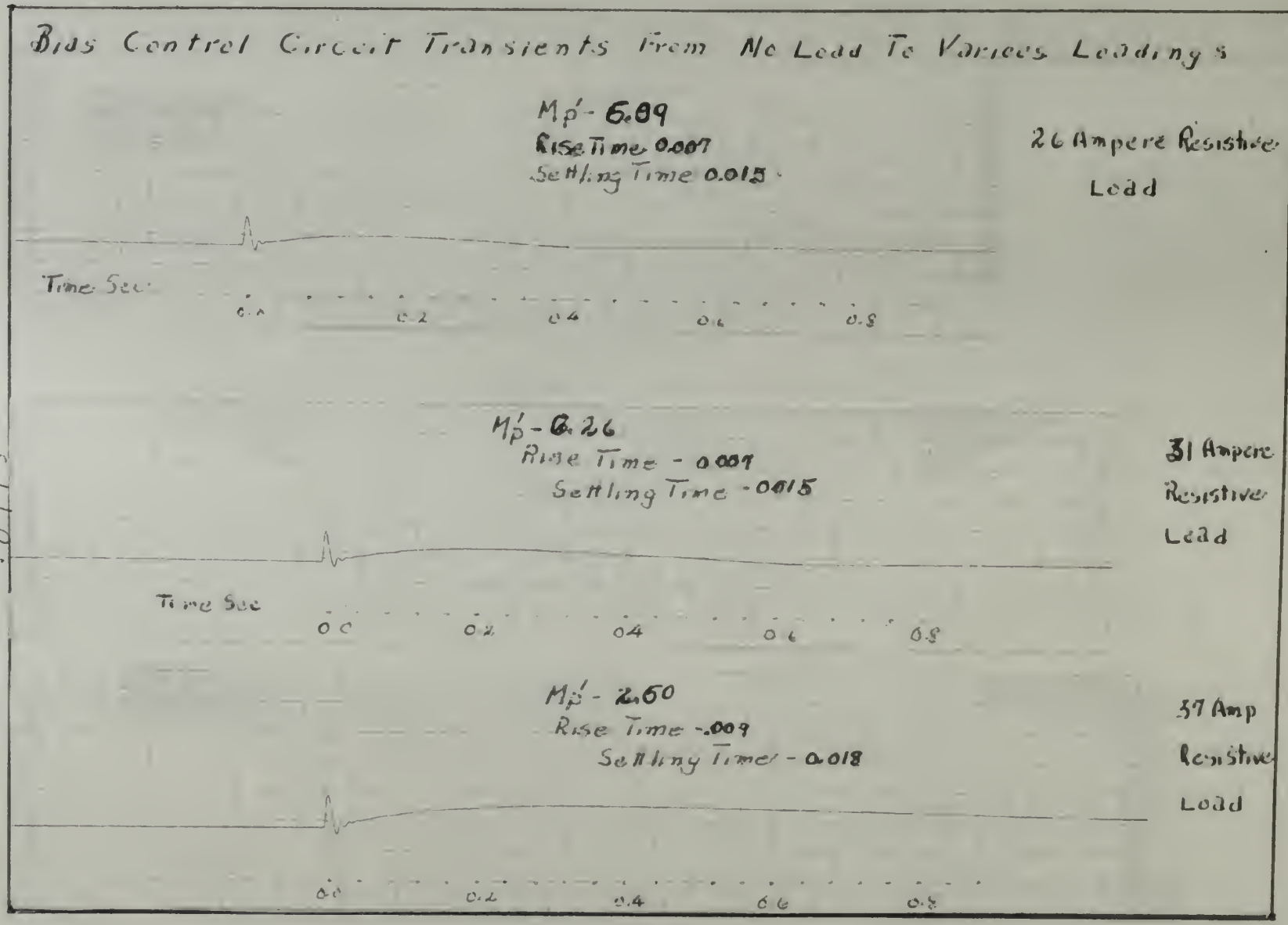

Bias Control Circuit Transients From No Load To Varices Loadings
Mp' - 6.09
Rise Time 0.007
Settling Time 0.015
26 Ampere Resistive Load
Time Sec
0.0
0.2
0.4
0.6
0.8
Mp' - 6.26
Rise Time - 0.009
Settling Time - 0015
31 Ampere Resistive Load
Volts
Time Sec
0.0
0.2
0.4
0.6
0.8
Mp' - 2.60
Rise Time - .009
Settling Time - 0.018
37 Amp Resistive Load
0.0
0.2
0.4
0.6
0.8

Figure 41

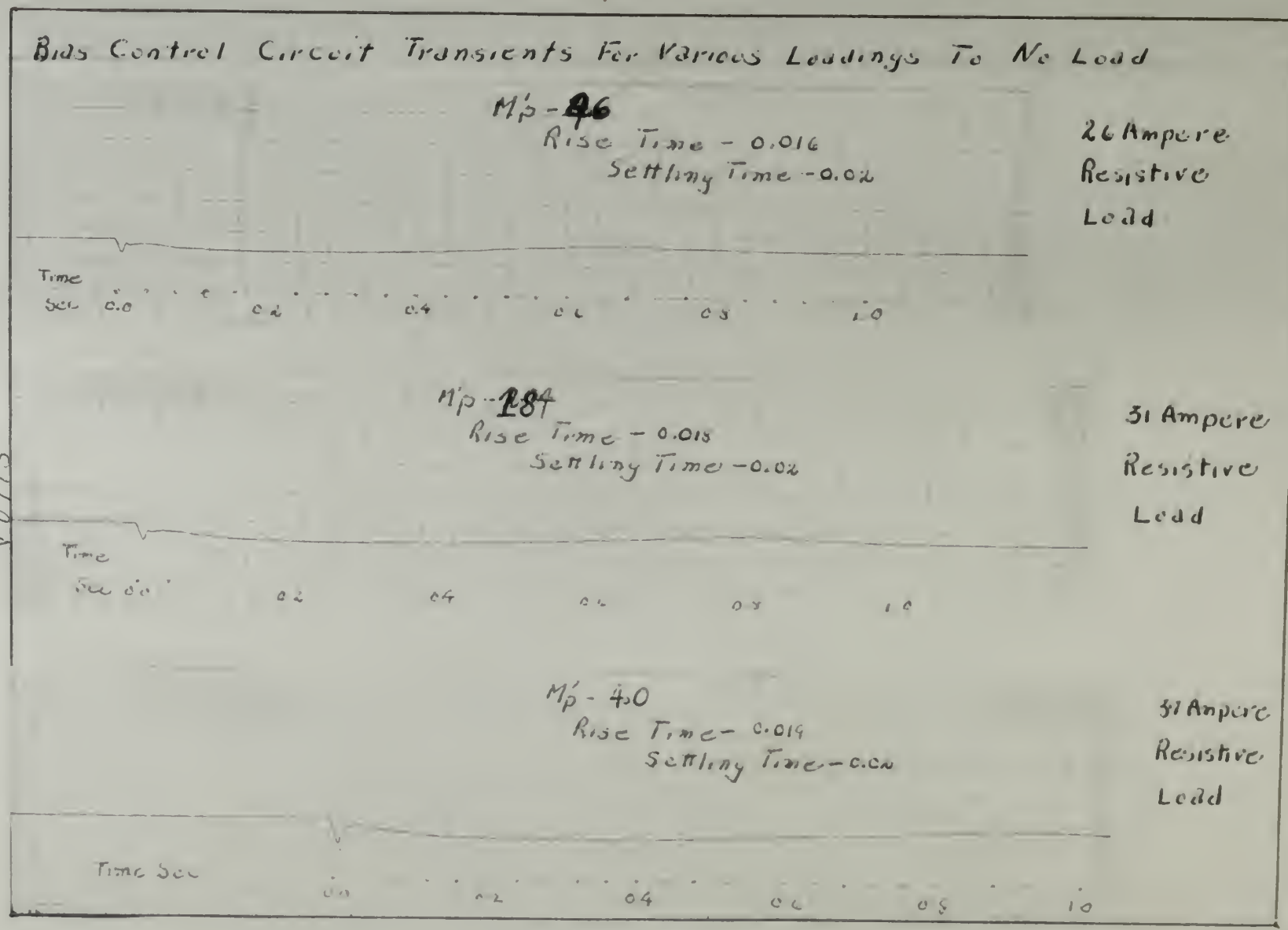
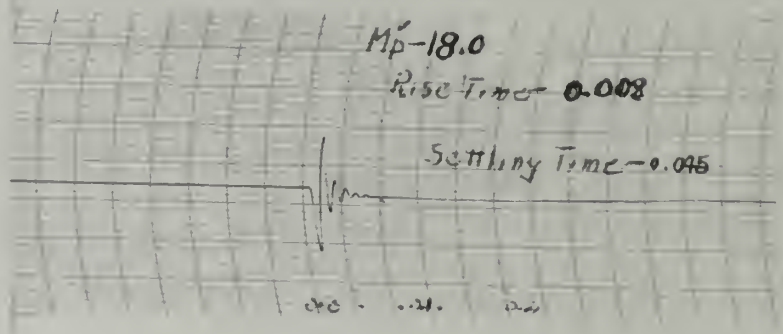
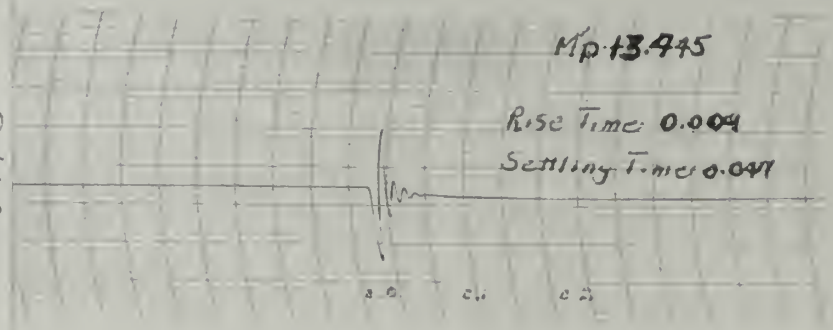

Bids Control Circuit Transients For Various Loadings To No Load
Mp - 46
Rise Time - 0.016
Settling Time - 0.02
26 Ampere Resistive Load
Time Sec 0.0 0.2 0.4 0.6 0.8 1.0
Mp - 184
Rise Time - 0.018
Settling Time - 0.02
31 Ampere Resistive Load
Volts
Time Sec 0.0 0.2 0.4 0.6 0.8 1.0
Mp - 430
Rise Time - 0.019
Settling Time - 0.02
31 Ampere Resistive Load
Time Sec 0.0 0.2 0.4 0.6 0.8 1.0

Figure 42

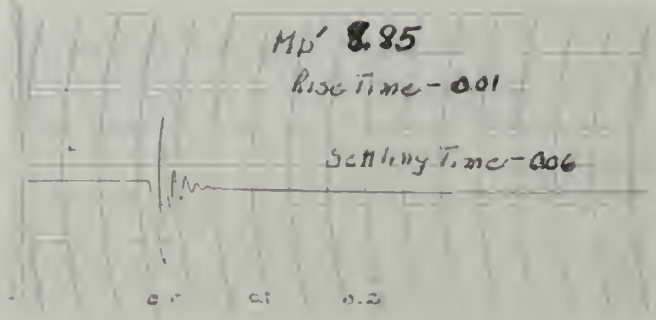
Preamplifier Control Circuit Transients from No Load To Varies Loadings



2 6 Ampere Resistive Load



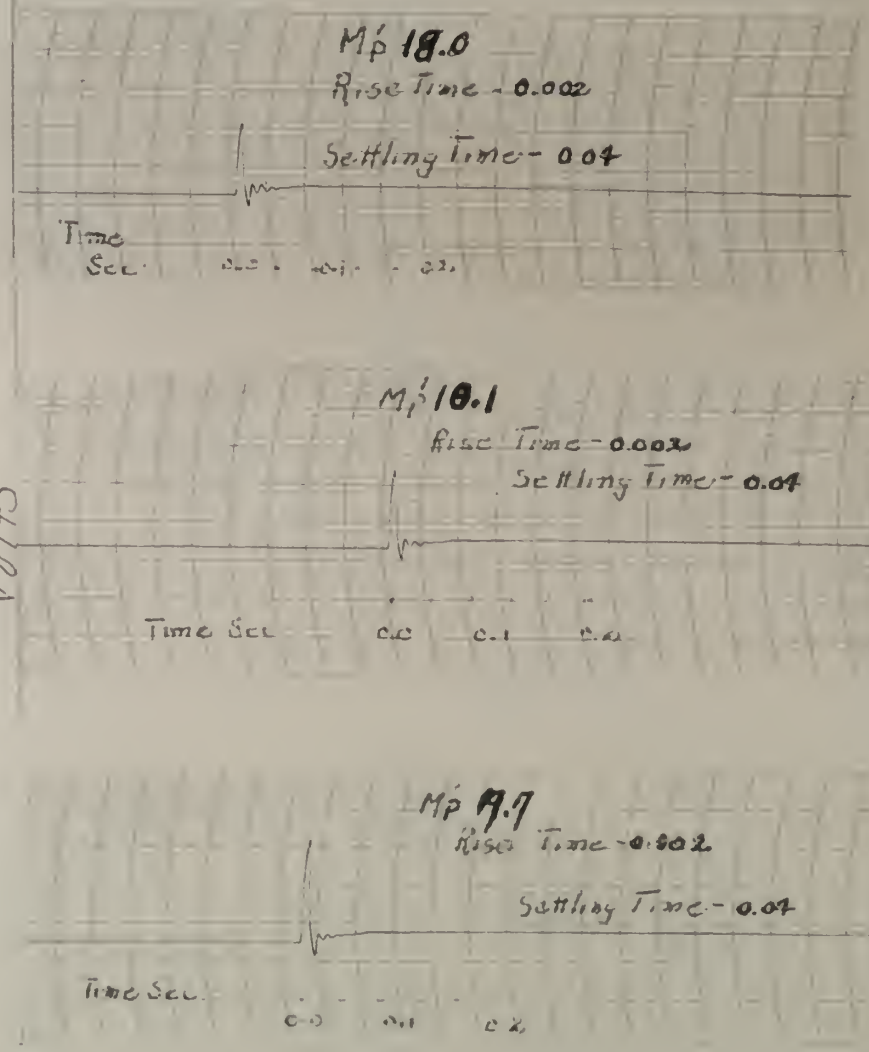
31 Ampere Resistive Load



37 Ampere Resistive Load

Figure 43

Preamplifier Control Circuit Transients For Various Loadings To No Load



26 Ampere Resistive Load

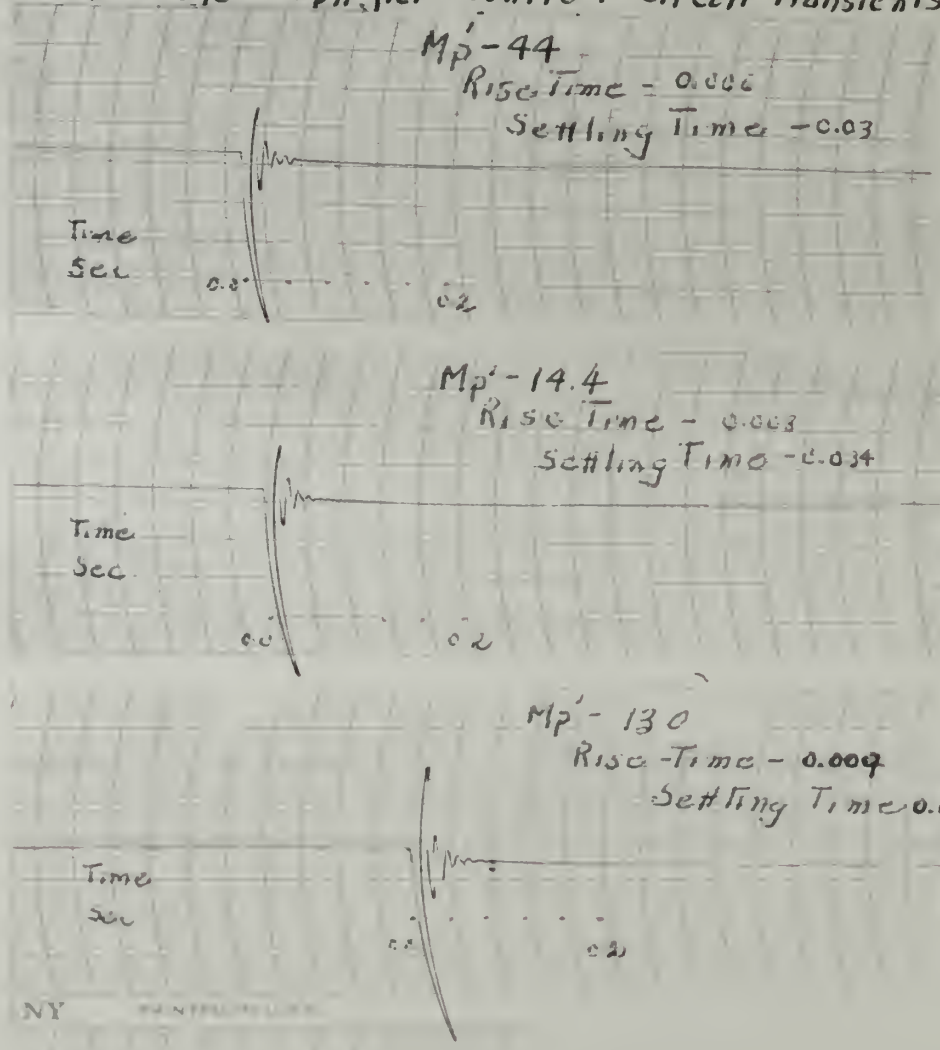
31 Ampere Resistive Load

37 Ampere Resistive Load

Figure 44

Page 91
Vol 75

Final Stage Amplifier Control Circuit Transients From No Load To Various Loadings



21 Ampere Resistive Load

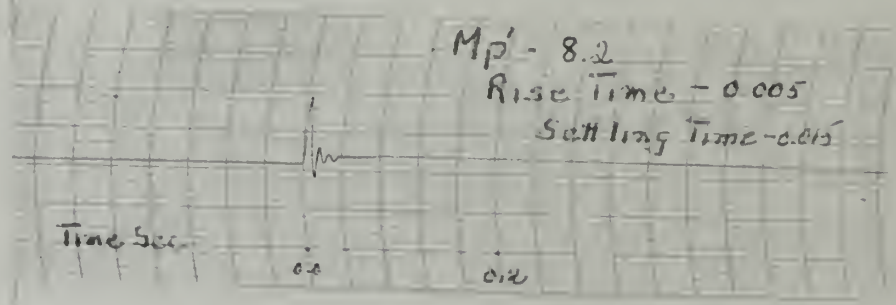
31 Ampere Resistive Load

37 Ampere Resistive Load

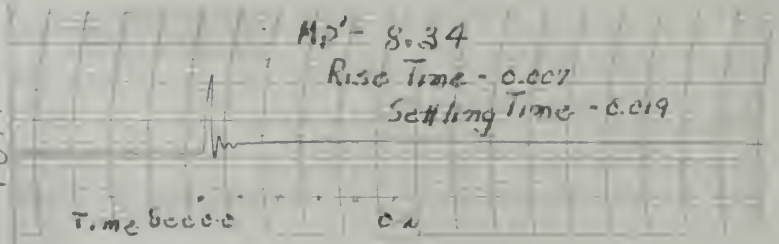
Page 92
Vol 4-5

Figure 45

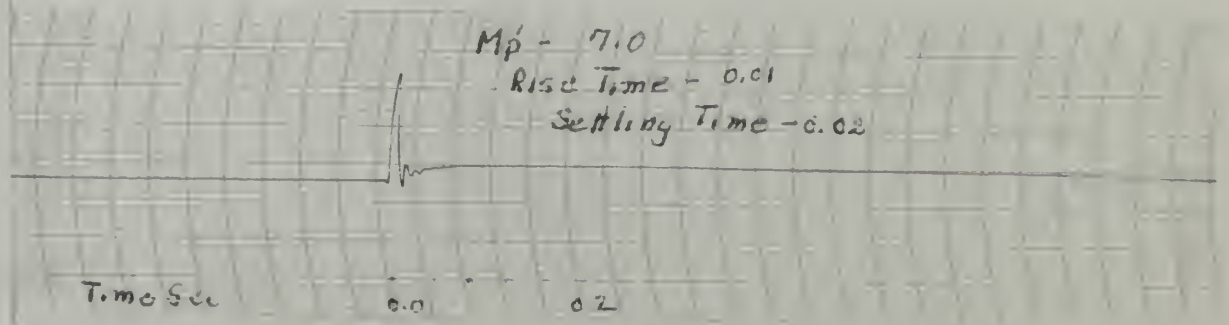
Final Stage Amplifier Control Circuit Transients For Various Loadings To No Load



26 Ampere Resistive Load



31 Ampere Resistive Load



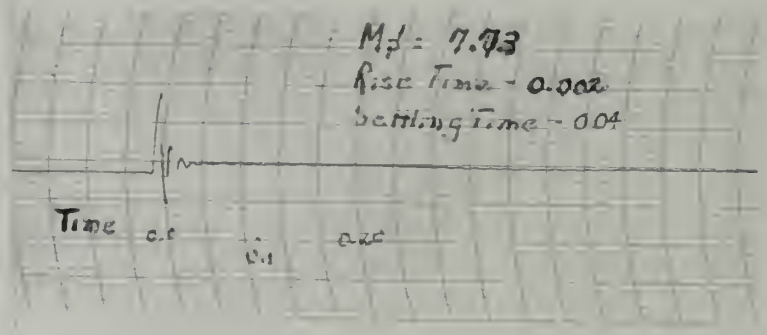
37 Ampere Resistive Load

Volts

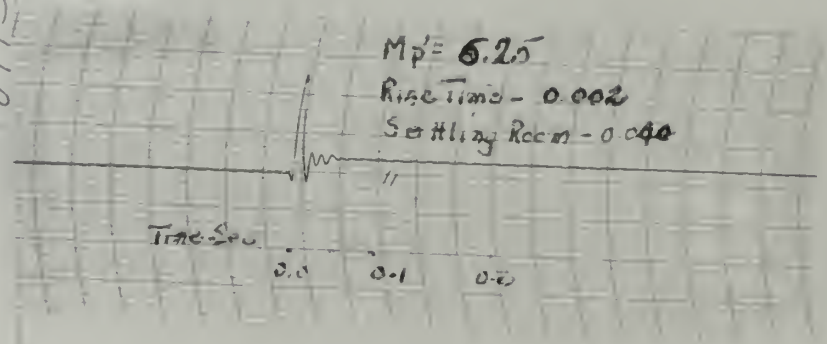
Page 93

Figure 46

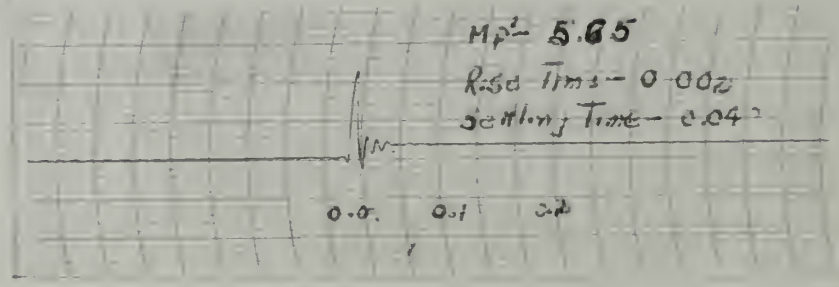
Final Stage Amplifier Main Power Transients From No Load To Varies Loading



23 Ampere Resistive Load



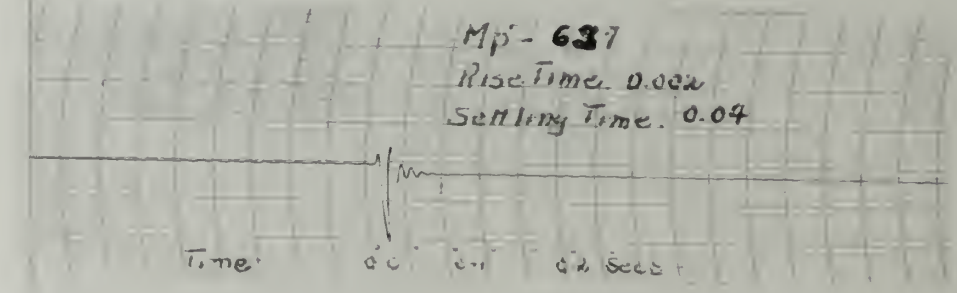
35 Ampere Resistive Load



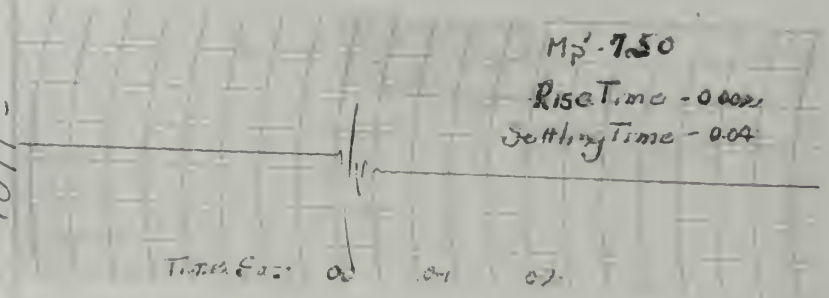
30 Ampere Resistive Load

Figure 47

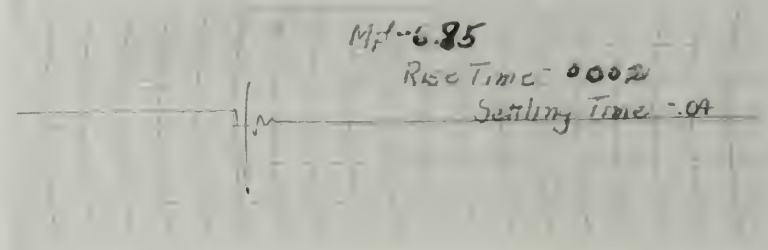
Final Stage Amplifier Main Power Transients For Various Loadings To No Load



25 Amperes Resistive Load



35 Ampere Resitive Load



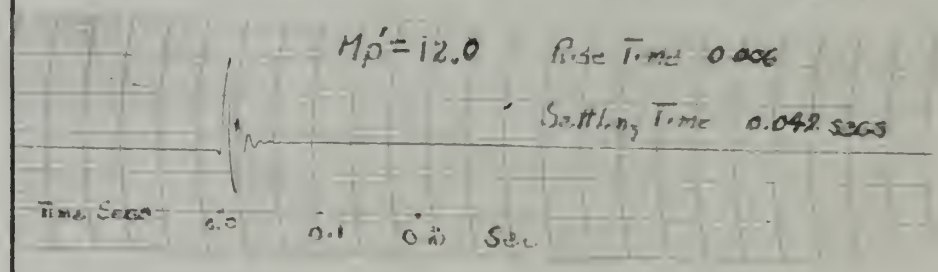
30 Ampere Resistive Load

Page 95

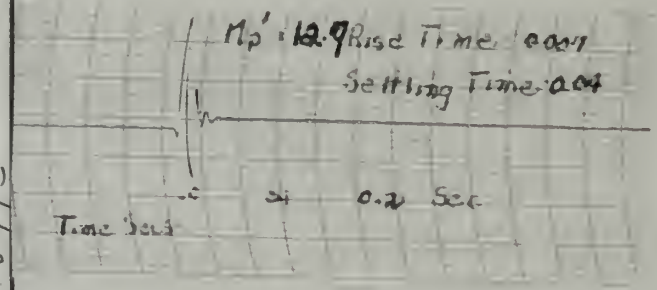
Page 96

Vol 175

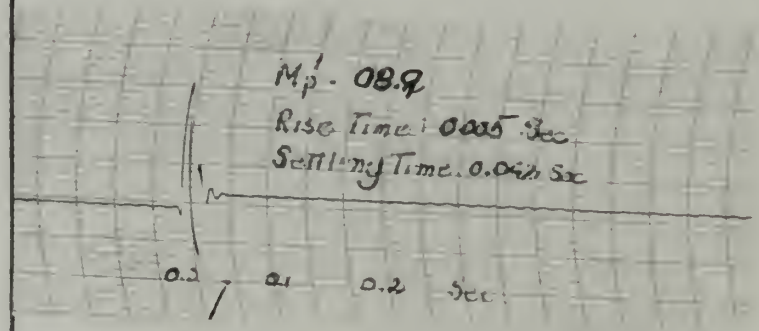
Generator Field Transients For No Load To Various Loadings



2.5 Ampere Resistive Load



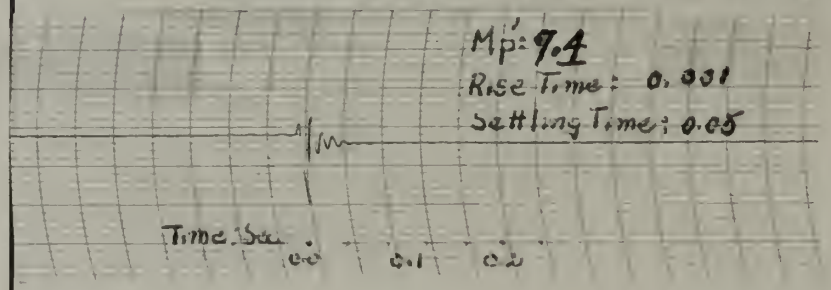
30 Ampere Resistive Load



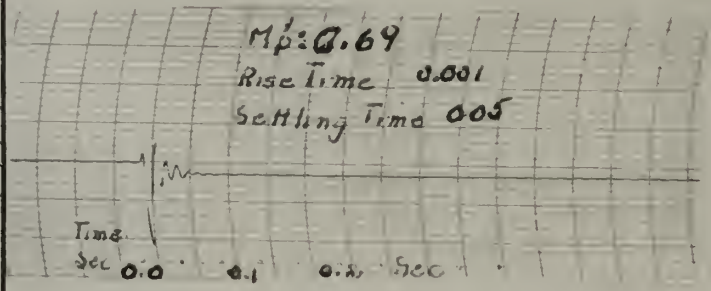
35 Ampere Resistive Load

Figure 49

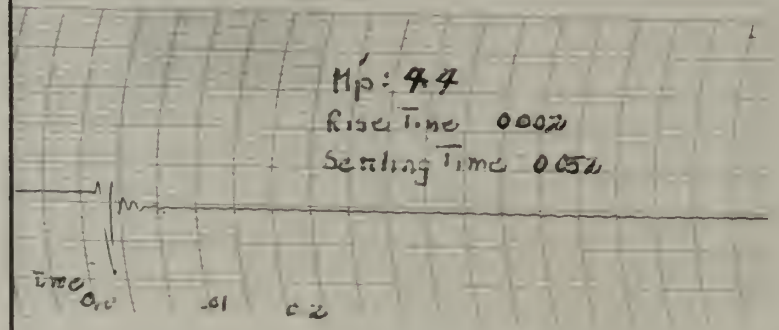
Generator Field Transients For Various Loadings To No Load



25 ampere resistive load



30 ampere resistive load



35 ampere resistive load

Figure 50

(D) The Significance of the Photographic Data.

The same procedure for analyzing the photographic data with reference to the junction points in figure 20A will be followed. It should be kept in mind at all times that the desirable output wave shape of the alternator is a sine wave with respect to both the voltage and the current. The means of securing this wave shape is by using as nearly aunidirectional non-pulsating direct current as may be obtained and by the proper design of the rotor and stator with respect to slots and windings. This is extremely brief in the statement of the resulting output wave shape, but it is stated only to reemphasize the importance of the functioning of the various components. It is to be noted that the very nearly perfect output voltage wave is realized, and there is only a very slight deviation in the current wave shape. These facts are indicated in figure 51 . The importance of the current and wave shape will be recognized when it is remembered that the voltage loop is sensitive to output voltage from the synchronous alternator, while the current loop is sensitive to line current. Now if these reference waves are practically pure sine waves, then the analysis is much simpler.

The Detector Transformer T1-27C61-2 characteristics are shown in figure 52 . The primary current wave is nearly a pure sine wave although there is a slight deviation in the primary voltage wave. This slight deviation is very likely due to the physical design of the stator and the method in which the mmf's add.

Now if the flux wave follows a sine wave, the current causing it is not likely to be sinusoidal but contains harmonics. These harmonics result from the saturation effect in the transformer. The only way in

which the current wave could be a sine wave would be to have a linear saturation curve. Now the secondary current and wave shape forms show the deviation from the true sine wave which is caused by the saturation of the core.

The output characteristics of the Tripler Reactor L1-38B55-2 are shown in figure 53 . The interesting point to be noted is that the output voltage is a very good sine wave while the current shows a definite harmonic composition. These output characteristics are elaborated on in detail later in this chapter.

The Rectifier 1-44B30-2 shows the rectified voltage and current which is the control characteristics of the Preamplifier 35C63-2. It is best to reemphasize at this point that we are concerned with current which is used to saturate the core. The current wave is a rectified complex wave, but the average current value for each cycle is uniform and periodic. Now notice the voltage wave which has a negative section.

These characteristics are duplicated in the Rectifier 1-44C190-2 shown in figure 54 . Even though the voltage goes negative the rectified current is positive. The average current is slightly less than the maximum value due to the fact that rectification is not effective for a full cycle. Nonetheless it is considered effective in this instance because this picture only represents one third of a unit. When the units are connected for three phase operation, a better pulsating current is obtained which has a periodic wave. The direct current level is high with a relatively small ac level. Now the input alternating current characteristics deviate only slightly from the pure sine wave.

Considering the Rectifier 2-44C79-2 which is the bias winding recti-

fier it is seen that the wave shapes of the input voltage and current deviate considerable from the pure sine wave. The current wave shape has a clipped section which indicates the possibility of saturation. This, however, may be a characteristic of this type of selenium dry disc rectifier which is operated in 3Ø half wave rectification. The output voltage shows a relatively low ripple factor and the direct current level is high. The current is the significant characteristic. It is pointed out that the current is an acceptable rectified direct current.

The successful degree of rectification of current in the three input currents is as follows:

(1) Bias current, 95% complete rectification.

(2) Control current, 85% complete rectification.

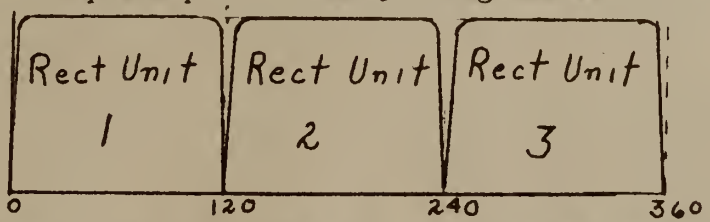
(3) Main power current, 80% complete rectification.

It is to be remembered that the output current wave form from the Preamplifier 35C63-2 which is shown in figure 57 is the resultant effect of the three input currents. It is true that the output current is the physical sum of the three main power phase rectification, but this wave shape is the result of the saturation effect on the core. Even with this effect present, the degree of rectification is 85%. It is also periodic which is a very desirable characteristic.

One of the characteristics of the rectifiers analyzed thus far is the fact that the voltage wave sometimes goes negative although the current wave is always positive with respect to the zero direct current level. This characteristic is most pronounced in the output voltage wave shape shown in figure 57 .

The characteristics of the rectifier unit RECT 44C20-2 are shown in

figure 56 . The input current and voltage wave shape show the pronounced effect of saturation. The input current resembles the desired rectified direct current; however, this characteristic was observed in the rectifier unit 2-44C79-2. The main consideration is the output current. As indicated in the picture, this unit has the highest degree of rectification. It is of the order of 97%. It must be remembered that the picture indicates only one third of the rectifier unit. In addition these rectifier units are connected such that the units are phase sensitive. In short, the complete picture for 360 degrees would be as follows:



The voltage wave is a complex wave, but it is to be noted that the voltage wave does not go negative thus indicating a better degree of rectification.

The output characteristics of the Final Stage Amplifier 35D96-2 are the main characteristics to be considered. It is the current which must be as nearly non-pulsating unidirectional as possible in order to secure a uniform field. Figure 64 shows the output characteristics of the Final Stage Amplifier which are also the generator field characteristics. It is shown that the direct current level of the current is high. In short, the generator field current is considered to be a highly rectified practically non-pulsating unidirectional current. The third picture in figure 64 shows that when the wave is magnified one hundred times there is an alternating current ripple. The degree of rectification is 99% effective. However, the voltage wave shape though periodic is a

very complex wave and goes negative in part.

Four different degrees of rectified current have been shown and it indicates that each degree of rectification is satisfactory to accomplish its purpose. This means that some units are used in order to get a better degree of rectification. However, the excitation for the magnetic particle clutch is rectified current, and the general wave shape approaches a sine wave. This is shown in figure 59 . It is realized that this wave has an average value which is steady as the rectified current wave shape is periodic. Thus the functioning of the magnetic particle clutch is not impaired.

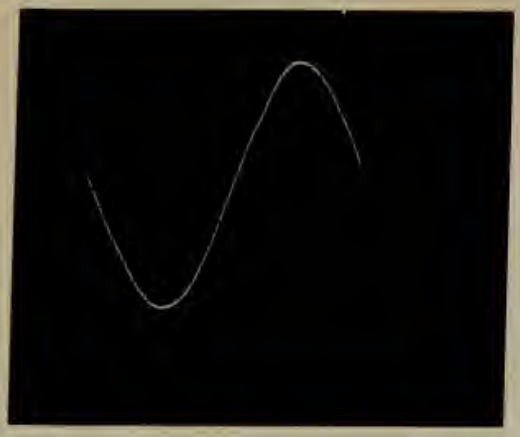
The output voltage of the tachometer permanent magnet generator is shown in figure 59 . This is presented to show that in direct current generators there may be a slight ripple in the voltage and current wave shapes.

Figure 63 shows the output voltage of Preamplifier 35C63-2. It is shown that the voltage goes negative for a part of the cycle although it is remembered that the current wave shape was never negative although there was a relatively high ripple factor.

Figure 64 shows effectively how the main power currents for the Final Stage Amplifier combine to give the desired unidirectional generator field current even though the generator field voltage is a pulsating type function with a few negative parts.

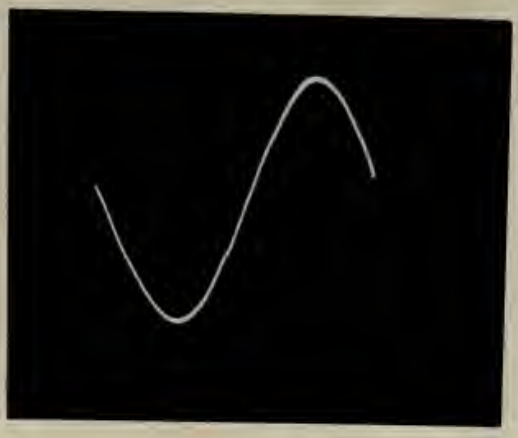
To indicate how the various cores may effect the output wave shapes refer to figure 57 . The main power voltage and the output voltage of the Preamplifier Stage 35C63-2 are shown. The saturation effect is most pronounced.

It will be recalled that earlier the output characteristics of the Tripler Reactor L1-38B55-2 were described. It was noted that even though the voltage wave shape was a sine wave, the current wave most definitely had harmonics introduced. Figures 60 , 61 , and 62 show transient wave shapes and steady state wave shapes for voltage. In figure 61 the steady state voltage is shown and it is to be noted that there is a very high degree of third harmonic voltage. The transient photographs indicate most emphatically the effect of a high degree of saturation in the core. Lastly the R C and R L type of transient are indicated in the composite transients.



Generator Output Voltage
No Load

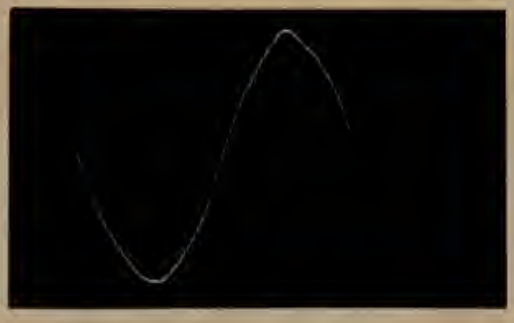
Generator Output Voltage
Full Load



Generator Load Current
at Full Load

Figure 51
Page 104

Primary Current of Detector Transformer T1 - 27C61-2



Primary Voltage of Detector Transformer T1 - 27C61-2

Secondary Voltage of Detector Transformer T1-27C61-2

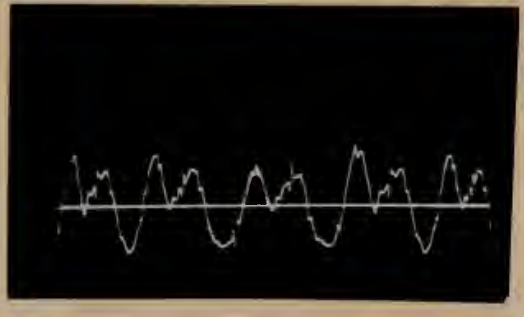
Secondary Current of Detector Transformer T1 - 27C61-2

Figure 52

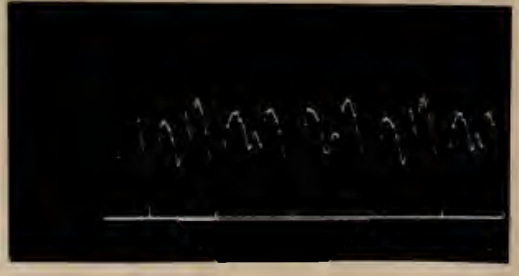
1-4

Output Voltage of Tripler
Reactor L1-38B55-2

Output Current of Tripler
Reactor L1-38B55-2



Output Voltage of Rectifier
Rect-1-44B30-2

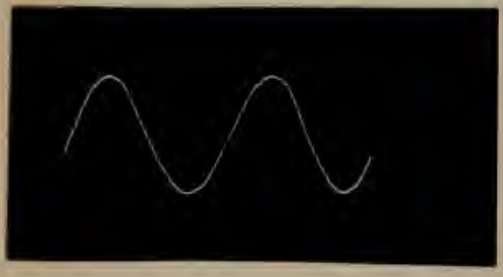


Output Current of Rectifier
Rect-1-44B30-2

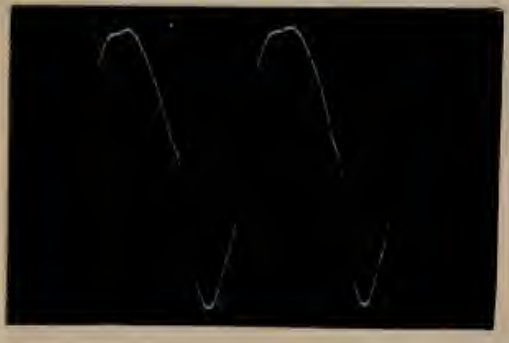
Figure 53
Page 106

Output Voltage From Rectifier 1-44C190-2 For Main Power Winding Preamplifier Stage 35C63-2.

Output Current From Rectifier Rect 1-44C190-2 For Main Power Winding Preamplifier Stage 35C63-2



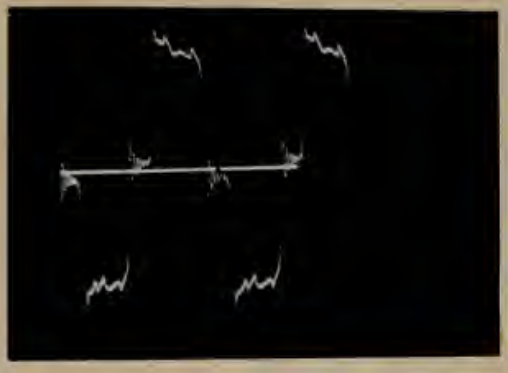
Input Voltage To Rectifier Rect 1-44C190-2



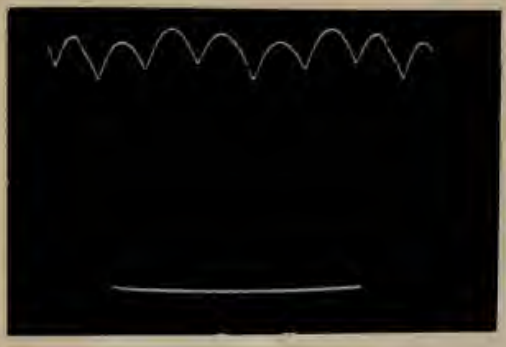
Input Current To Rectifier Rect 1-44C190-2

Figure 54

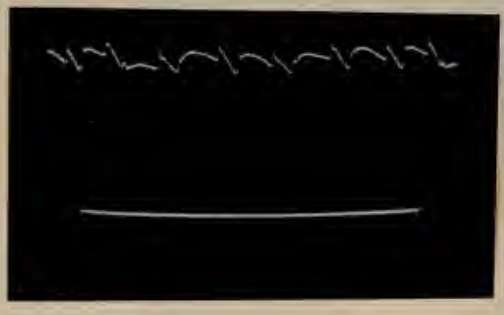
Input Voltage To Rectifier
Rect 2-44C79-2



Input Current To Rectifier
Rect 2-44C79-2



Input Voltage To Bias Power
Winding of Preamplifier
Stage 35C63-2

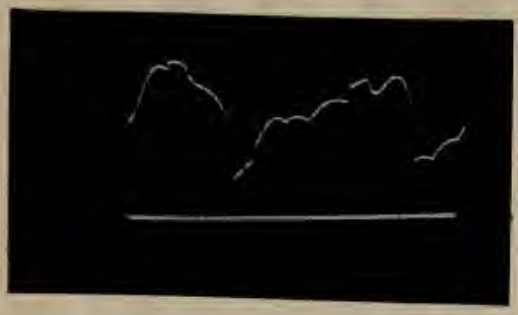


Input Current To Bias Power
Winding of Preamplifier
35C63-2

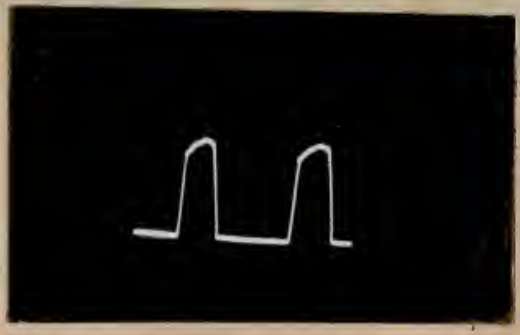
Figure 55

Input Voltage To Rectifier Unit 44C20-2 For Final Stage Amplifier 35D96-2

Input Current To Rectifier Unit 44C20-2 For Final Stage Amplifier 35D96-2



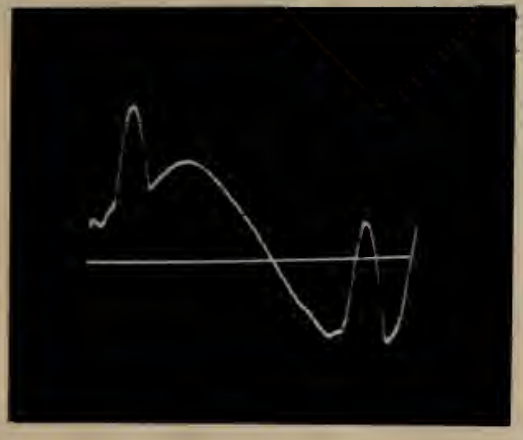
Output Voltage From Rectifier Unit 44C20-2 For Final Stage Amplifier 35D96-2 Which is The Main Power Current For The Final Stage



Output Current From Rectifier Unit 44C20-2 For Final Stage Amplifier 35D96-2 Which is The Main Power Voltage For The Final Stage

Figure 56

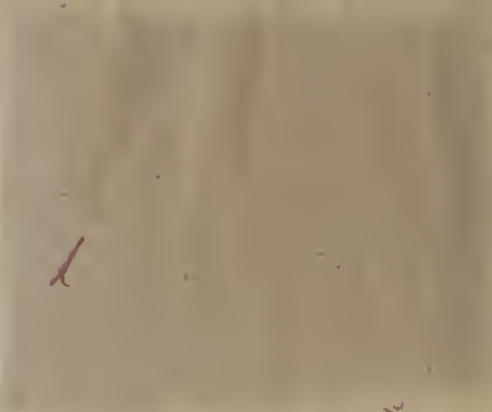
Input Current To Bias Power Winding of Preamplifier 35C63-2



Output Voltage of Preamplifier Stage 35C63-2

Output Current of Preamplifier Which is The Control Current For The Final Stage Amplifier 35D96-2

Figure 57



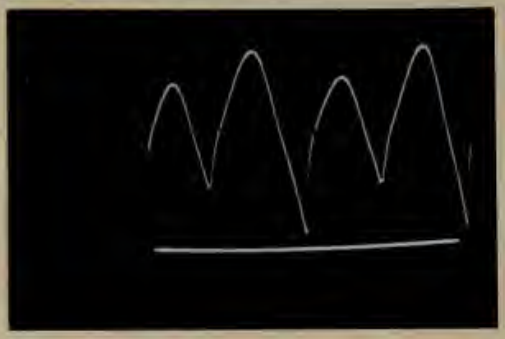
Generator Field Voltage

Generator Field Current

Expanded View of Generator Field Current

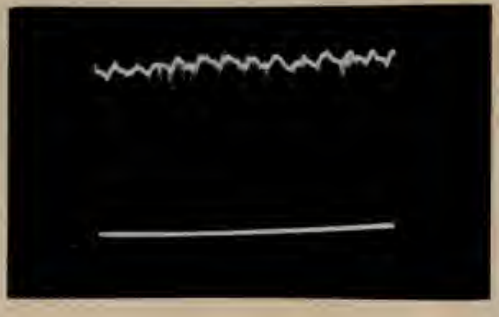
Figure 58

Magnetic Clutch Voltage



Magnetic Clutch Current

Induction Motor Current



Tachometer Voltage

Figure 59

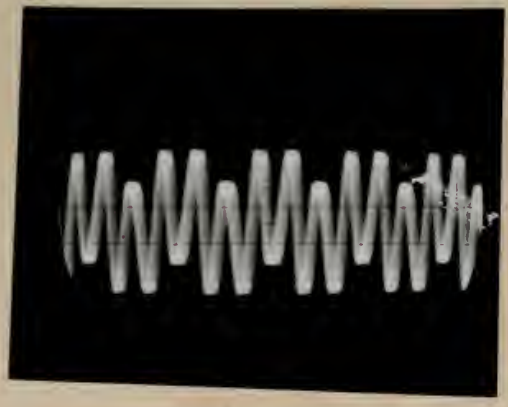
Sweep Range Time
Per Cm.
10-30 u sec.

Figures 60, 61, and 62 show the effect of the voltage step function of the tripler reactor component. These transients were photographed on a Textronix Inc., Portland, Oregon Type 512 cathode Ray Oscilloscope Serial 1222 using the Dumont-Bolsey Oscillograph Record camera Type 296 Serial 6x98 - Lense Raptar No 967816 - Wollensak 41.5mm f/2.8 Kodak Super Double XX film was used. The settings on the camera were bulb and f/2.8 The various sweep range settings are indicated opposite each picture.

Figure 60
Page 113

Sweep Range Time Per Cm
30 millisec — .1 sec

Sweep Range Time Per Cm
10-30 millisec



Steady State Output Voltage
Composed of Fundamental
and Large Third Harmonic

Tripler Reactor Voltage Transients
Figure 61
Page 114

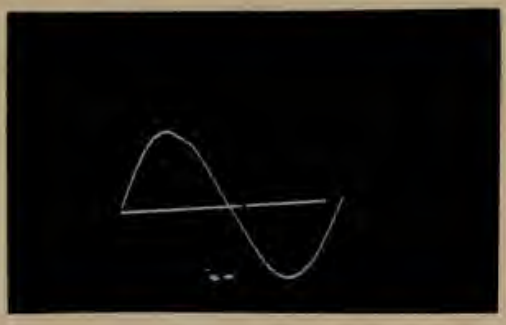
Sweep Range Time Per Cm.
30 u sec - 0.1 millisec

Sweep Range Time Per Cm.
1-3 millisec

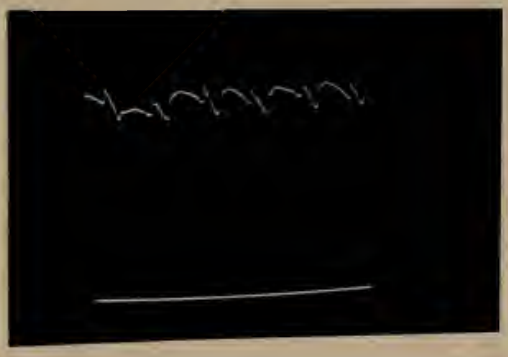
Sweep Range Time Per Cm
3 - 10 millisec

Tripler Reactor Voltage Transients
Figure 62
Page 115

Input Current To
Rectifier Rect 2-44C79-2
Bias Current.



Input Voltage To
Rectifier Rect 2-44C79-2
Bias Voltage



Bias Current To
Bias Winding of
Preamplifier 35C63-2
Rectified Current- Full Wave

Output Voltage For
Preamplifier Stage 35C63-2
D.C.

Figure 63
Page 116

Main Power Input Current To Final Stage Amplifier 35D 96-2

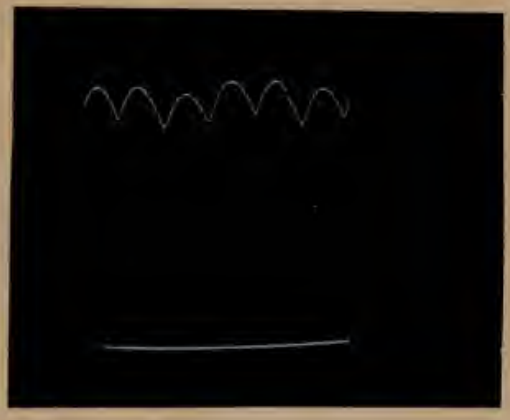
Output Current From Final Stage Amplifier 35D 96-2 Which Is The Generator Field Current

An Expanded View of The Generator Field Current

Output Voltage Final Stage - Generator Field Voltage

Figure 64

Expanded View of The Input Voltage To Main Power Winding of Preamplifier Stage 35C63-2



Input Voltage To Main Power Winding of Preamplifier Stage 35C63-2

Output Voltage of Preamplifier Stage 35C63-2

Figure 65

CHAPTER VII

CONCLUSIONS AND DISCUSSIONS OF RESULTS

This research was prompted by the Bureau of Ships' enclosure, which was quoted in Chapter II. Whereas the answers to many of the questions asked must remain unanswered, it is unhesitatingly stated that some of the questions can be answered in part. Nonetheless from this investigation, it is felt that the answers are obtainable in a generalized form which may be applied to specific situations.

The answers that are given will be based on the study just completed. No attempt will be made to answer the questions from a motor, magnetic particle clutch, speed regulator, voltage regulator, and synchronous point of view. Rather the answers will refer to the synchronous generator and voltage regulator as indicated in the block diagram, figure 20-A.

Question 1. Which machine characteristics of the motor and generator used in a motor generator must be known to permit the design and construction of the voltage regulator before they are available to experiment with?

Answer: The generator characteristics for the synchronous alternator which must be known are:

a. The saturation curve, magnetization curve, for the synchronous speed from zero field current to twice no lead field current.

b. The voltage regulation curves of the synchronous generator from 70% rated terminal voltage to 125%

rated terminal voltage.

c. The general specifications which define the synchronous alternator, i.e.:

Main Specifications:

Capacity, K W	Terminal Volts, full load
Power factor	Amperes line, full load
Capacity	Regulation at P. F.
Number of phases	Frequency
Type of coupling	Maximum allowable temperature rise

Secondary Specifications:

Type of pole construction	Mean gap density
Pitch factor	Type of internal connections
Ratio of Pole arc to Pole Pitch	Differential factor
Peripheral current density	Leakage reactance drop per phase volt

Question 2. How can we measure these characteristics?

Answer: a. The magnetization curve for the synchronous alternator may be obtained by separately exciting the alternator field and recording the terminal voltage and field current: Figure 22 .

b. The voltage regulation curves for the synchronous generator are obtained by separately exciting the synchronous alternator to the desired terminal voltage and then loading the synchronous alternator. Figure 21 .

c. The general specifications which define the synchronous alternator are always known, and these quantities can usually be readily verified.

Question 3. How closely must the range of permissible values for the machine characteristics be specified in order to avoid the necessity of building an excessive range of adjustment into the voltage regulator?

Answer: It is felt that the manufacturers could build a machine with the desired characteristics and very close tolerances. It wouldvery likely be extremely expensive compared to the conventional design. The same characteristics would have to be evaluated and their range would be known. Nonetheless the necessary corrective action of the voltage regulator would be known from the regulation curve in order to obtain constant terminal voltage. It is considered more feasible to have a wider range of operation in the voltage regulator to compensate for normally acceptable synchronous generators than spend great sums in trying to improve inherent regulation in the synchronous generator.

Question 4. Can the machine designers design their machines with sufficient accuracy so that we can be sure the machines will actually have machine characteristics within the specified ranges of values?

Answer. It is felt that the art of machine design certainly has reached the state where the machine designers can pre-

dict what the machine characteristics will be within the specified ranges of values.

Question 5. If I know the specified performance characteristics for the complete unit, what values must be specified for the machine characteristics in order to arrive at an optimum design for the complete unit considering weight, space, cost, and other pertinent factors.

Answer. It would require a most intensive study to arrive at an optimum design. First, it would require a clearly defined priority of optimizing characteristics. Secondly, it must be decided what the optimum value for each characteristic is. Lastly, it must be confirmed that the various optimized characteristics are compatible. For instance, the minimum cost is not necessarily compatible with weight and space.

The Bureau of Ships' letter was indeed a thought provoking questionnaire, but it can be answered and will be answered in time. Now refer to the voltage regulator system:

1. The application of linear servomechanism theory is feasible.
2. A proposed transfer function relating the generator field current and the line current has been formulated. This represents the first approximation until this transfer function has been evaluated.
3. The various characteristics and components are not all linear. The three categories are classified below:

   A. The following characteristics and components possess linear

characteristics.

1. The normal operating region of the magnetization curve is linear.
2. The Detector Transformer T1-C766-2
3. Bias Rectifier 2-44C79-2
4. Preamplifier 35C63-2
5. Main Power Rectifier 44C20-2
6. Final Stage 35D96-2

B. The following components deviate only slightly from a linear characteristic thus permitting the utilization of linear theory.

1. Tripler Reactor Li-38B55-2
2. Rectifier RECT 1-44B30-2

C. The following component, Current Transformer 27C68-2, deviates considerably from a linear characteristic; however, sectional linear application is feasible.

4. The transient characteristics of the units analyzed apparently present an unusual concept in servomechanism theory. The correlation between the Mp', the rise time, andthe settling time must be investigated further.

5. The very high values of Mp's must be evaluated more completely in order to relate this to known standards. If this is not feasible, then new definitions must be accepted to define properly this phenomena.

6. The Magnetic Amplifiers can be considered as gain devices with linear characteristics.

7. The various rectifiers used do not have the same rectifying characteristics. Thus, the degree of rectification depends on the application of the applied rectified current. As evidenced by the generator field current, the nearly non-pulsating unidirectional current is realized.

8. The overall voltage regulator system is very well designed from a steady state and transient operation view point. It will hold terminal voltage constant through 130% full load. It can be step functioned through 140% full load current and still operate within designed limits.

9. The specific characteristics of the voltage regulator which make it operate effectively are:

   A. It is very sensitive to voltage andcurrent changes.

   B. The current loop tends to regulate independently of the voltage loop, thus having the effect of a regulator and an anti-hunt - dampening device.

   C. The physical design of the various building blocks is such that for a given load change, the corrective incremental field current is supplied with the proper polarity.

CHAPTER VIII

RECOMMENDATIONS FOR FURTHER STUDY

The most that this thesis could accomplish was to set up the equipment, adjust it as necessary to insure proper operation, investigate the inherent characteristics of the generator and voltage regulator, and analyze the results obtained. This investigation was accomplished. There are, however, many many more problems yet to be solved before the Bureau of Ships' questions can be fully answered.

First, a proposed transfer function relating the generator field current and the synchroneous alternator's output current has been stated. This was developed as indicated in Appendix II. However, there is much work to be done in obtaining numbers for this transfer function. The physical parameters of the system must be evaluated. Finally, there is no definite assurance that the proposed transfer function represents the best expression for the system; revisions may be necessary and describing functions may be needed to replace some of the transfer functions.

A study of the magnetic amplifiers themselves is in order. It would be a relatively easy matter to determine the parameters of the magnetic amplifier and see what better arrangement might be used in accomplishing the amplification. Since the output current of the final magnetic amplifier stage is basically a triple function relationship of main power current, control current, and bias current, it would seem in order to determine exactly what these relationships are.

The references which were utilized in becoming familiar with the characteristics of the subject of magnetic amplifiers and rectifier are

listed in the Bibliography.

Transient tests, particularly those evaluated at intermediate points in the system, indicate that the damping criteria associated with basic servomechanism theory may not be applicable to the operation of the voltage regulator. Therefore, it seems likely that a study of the importance of transient overshoot, resonant frequency, settling time in voltage regulators, should be made. This study might even be extended to the fundamental problem of determining performance criteria for the general class of type zero servomechanisms.

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APPENDIX I

INSTRUMENTS USED IN RECORDING DATA

a - Weston Electrical Instrument Corporation Ammeter, Model 433, Scale 5/20/50 A C Amps, Cycles 5 - 500.

b - Roller Smith Co. Voltmeter, Type N P, A C Scale 0-750 volts, Frequency 15 to 100 cycles.

c - Weston Electrical Instrument Corporation, Model 931, Serial 7845, Scale 0-3.0 amperes direct current ammeter.

d - Weston Electrical Instrument Corporation, D. C. Voltmeter, Model 931, Serial 5550, Scale 0-15 volts.

e - Weston Electrical Instrument Corporation AC Ammeter, Model 433, Serial 81921, Frequency 25 - 500 cycles, Scale 0-250 Milliamperes.

f - Weston Electrical Instrument Corporation AC Voltmeter, Model 433, Number 94411, Frequency 25 - 500 cycles, Scale 0-150 volts.

g - Weston Electrical Instrument Corporation AC Ammeter, Model 433, Serial Number 81897, Frequency 25 - 500 cycles, Scale 0-250 milliamps.

h - Weston Electrical Instrument Corporation AC Voltmeter, Model 433, Serial Number 61192, Scale 0-150V, Frequency 25 - 2400 cycles.

i - Weston Electrical Instrument Corporation AC Ammeter, Model 433, Number 84428, Scale 0-100 ma, Frequency 25 - 500 cycles.

j - Weston Electrical Instrument Corporation AC Voltmeter, Scale 0-150 volts, Type 433, Frequency 25 - 2400.

k - Westinghouse DC Ammeter, Type PX - 4, Serial 2357166, Scale 0-50 milliamps.

l - Westinghouse DC Voltmeter, Type PX - 4, Serial 2357130, Scale 0-50 volts.

m - Weston Electrical Instrument Corporation AC Ammeter, Model 433, Serial 94436, Frequency 25 - 500 cycles, Scale 0-100 milliamps.

n - Weston Electrical Instrument Corporation AC Voltmeter, Model 433, Serial Number 61115, Scale 0-150 volts, Frequency 25 - 2400 cycles.

o - Weston Electrical Instrument Corporation DC Ammeter, Type 931, Serial 8671, Scale 0-150 ma.

p - Westinghouse Type PX - 4, DC Voltmeter, Scale 0-50 volts, Serial 2357107.

q - Weston Electrical Instrument Corporation DC Ammeter, Model 931, Serial Number 8683, Scale 0-150 milliamperes.

r - Weston Electrical Instrument Corporation DC Voltmeter, Model 45, Serial Number 62427, Scale 0-300 volts.

s - Weston Electrical Instrument Corporation DC Ammeter, Model 931, Serial Number 8536, Scale 0-250 milliamps.

t - Weston Electrical Instrument Corporation DC Voltmeter, Model 45, Serial Number 62416, Scale 0-300 volts.

u - Weston Electrical Instrument Corporation AC Ammeter, Model 433, Serial Number 81714, Frequency 25 - 500 cycles, Scale 0.0-2.0 amperes.

v - General Electric AC Voltmeter, Type AP - 9, Serial Number 1111322, Scale 0-300 volts.

w - Weston Electrical Instrument Corporation DC Ammeter, Model 45, Serial Number 52765, Scale 0-1.5 amperes.

x - Weston Electrical Instrument Corporation DC Voltmeter, Model 45,

Serial 62418, Scale 0-300 volts.

y - Weston Electrical Instrument Corporation DC Ammeter, Model 931, Serial Number 8552, Scale 0-30 amperes.

z - Weston Electrical Instrument Corporation DC Voltmeter, Model 931, Serial Number 5543, Scale 0-150 volts.

aa- Weston Electrical Instrument Corporation AC Ammeter, Model 433, Serial Number 87484, Scale 5/20/50 amperes, Frequency 25 - 500 cycles.

bb- Weston Electrical Instrument Corporation AC Voltmeter, Serial number 61135, Scale 0-150 volts, Frequency 25 - 2400 cycles.

cc- Weston Electrical Instrument Corporation Wattmeter, Serial Number 752, 7.5 - 15 KW, 150 - 300 V, 75 amps.

dd- Weston Electrical Instrument Corporation AC Ammeter, Model 433, Serial 87480, Scale 5/20/50 amperes, Frequency 25 - 500 cycles.

ee- Weston Electrical Instrument Corporation AC Voltmeter, Serial Number 60030, Scale 0-150 V, Frequency 25 - 2400 cycles.

ff- Weston Electrical Instrument Corporation Wattmeter, Serial 749, 7.5 - 15.0 KW, 150 - 300 V, 75 amps.

gg- Weston Electrical Instrument Corporation AC Ammeter, Model 433, Serial 104706, Scale 5/20/50 amperes, Frequency 25 - 500 cycles.

hh- Weston Electrical Instrument Corporation AC Voltmeter, Serial 61158, Scale 0-150 volts, Frequency 25 - 2400 cycles.

ii- Permanent Magnet Generator, Serial 672, RPM 6000, Terminal Products Company of Racine, Wisconsin.

jj- DC Amplifier, Model BL - 932, Mfg. by The Brush Development Co.

kk- Direct Inking Oscillograph, Model BL 202, Mfg. by The Brush Dev-

elopment Co.

11- Tektronix Inc. Type 512, Cathode Ray Oscilloscope, Serial 1222.

mm- Dumont Belsey Oscillograph Record Camera, Type 296, Serial 6X98, Raptar Number 967816 Wollensak 415mm f/28

nn- Hewlett Packard Frequency Counter, Model 524A, HP Meter AN/TSM-9.

APPENDIX II

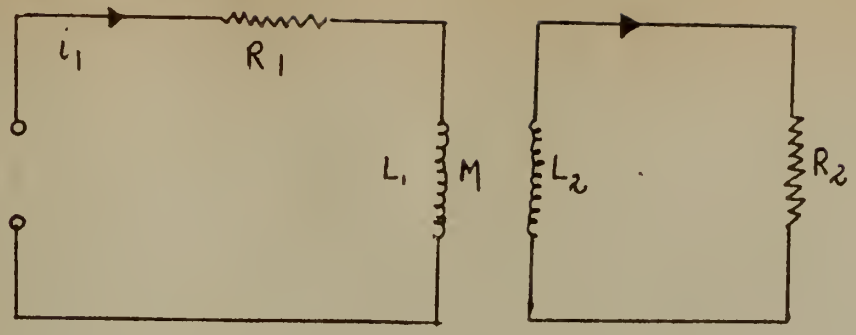
Derivation of Transfer Functions for the Various Components in the Voltage Regulator System.

(A) Transformer

(B) Full Wave Rectifier

(C) Tripler Reactor

The Transformer:



$$M = k\sqrt{L_1 L_2}$$

For U (t) to primary then current response in secondary goes to a maximum then back to zero while the primary increases from zero to a value dependent on the primary resistance.

$$1 = R_1 i_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$$

$$0 = R_2 i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$

Take transform:

$$\frac{1}{s} = R_1 \bar{i}_1 (s) + L_1 s\bar{i}_1(s) - L_1 i_1 (o) + Ms\bar{i}_2 (s) - M i_2(0)$$

$$0 = R_2 \bar{i}_2 (s) + L_2 s \bar{I}_2 (s) - L_2 i_2 (0) + M s \bar{i}_1 (s) - M i_1 (0)$$

Rearranging the above equations:

$$\frac{1}{s} + L_1 i_1 (0) + M i_2 (0) = (R_1 + L_1 s) \bar{i}_1 (s) + M s \bar{i}_2 (s)$$

$$L_2 i_2 (0) + M i_1 (0) = M s \bar{i}_1 (s) + (R_2 + L_2 s) \bar{i}_2 (s)$$

The numerator determinant for the primary current

$$\bar{i}_1(s) = \frac{\begin{vmatrix} \left(\frac{1}{s} + L_1 i_1(0) + M \bar{i}_2(0)\right) & (M\ s) \\ \left(L_2 i_2(0) + M i_1(0)\right) & (R_2 + L_2 s) \end{vmatrix}}{\begin{vmatrix} (R_1 + L_1 s) & (M\ s) \\ (M\ s) & (R_2 + L_2 s) \end{vmatrix}}$$

$$\bar{i}_2(s) = \frac{\begin{vmatrix} (R_1 + L_1 s) & \left(\frac{1}{s} + L_1 i_1(0) + M i_2(0)\right) \\ M\ s & (L_2 i_2(0)\ \ M i_1(0)) \end{vmatrix}}{D}$$

$$\frac{\bar{i}_2(s)}{i_1(s)} = W_T(s) = \frac{\begin{vmatrix} (R_1 + L_1 s) & \left(\frac{1}{s} + L_1 i_1(0) + M i_2(0)\right) \\ (M\ s) & (L_2 i_2(0) + M i_1(0)) \end{vmatrix}}{\begin{vmatrix} \left(\frac{1}{s} + L_1 i_1(0) + M i_2(0)\right) & (M\ s) \\ \left(L_2 i_2(0)\ \ M i_1(0)\right) & (R_2 + L_2 s) \end{vmatrix}}$$

$$W_T(s) = \frac{\left[R_1 L_2 i_2(0) + R_1 M i_1(0) + L_1 L_2 i_2(0)s + L_1 M i_1(0)s\right] - \left(M + M L_1 i_1(0)s + M^2 i_2(0)\ s\right)}{\left(\frac{R_1}{s} + R_2 L_1 i_1(0) + R_2 M i_2(0) + L_2 + L_2 L_1 i_1(0)\ s + M L_2 i_2(0)\ s\right) - M L_2 i_2(0)\ s - M^2 i_1(0)\ s}$$

$$W_T(s) = \frac{s\left\{s\left[L_1 L_2 i_2(0) + L_1 M i_1(0) - M L_1 i_1(0) - M^2 i_2(0)\right] + \left[R_1 L_2 i_2(0) + R_1 M i_1(0) - M\right]\right\}}{s^2\left\{L_2 L_1 i_1(0) + M L_2 i_2(0) - M L_2 i_2(0) - M^2 i_1(0)\right\} + s\left\{R_2 L_1 i_1(0) + R_2 M i_2(0) + L_2\right\} + R_2}$$

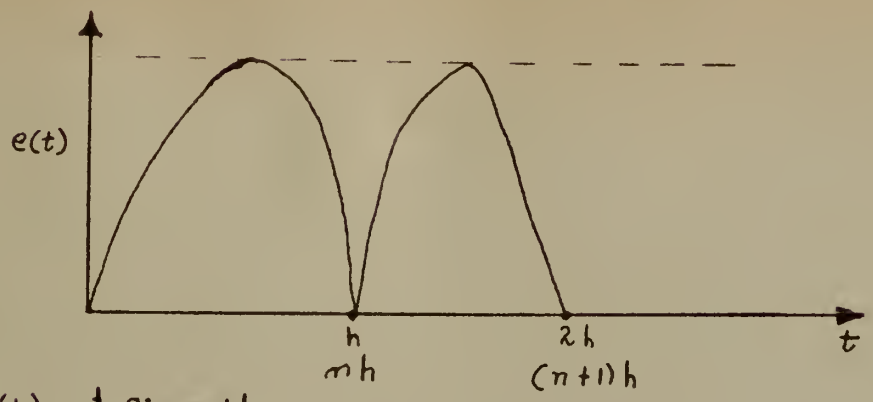
Transfer Function with initial conditions included

$$W_T(s) = \frac{s\left\{s\left[L_1 L_2 i_2(0) - M^2 i_2(0)\right] + \left[R_1 L_2 i_2(0) + R_1 M i_1(0) - M\right]\right\}}{s^2\left[L_2 L_1 i_1(0) - M^2 i_1(0)\right] + s\left[R_2 L_1 i_1(0) + R_2 M i_2(0) + L_2\right] + R_2}$$

Transfer Function with initial conditions

$$W(s) = \frac{s(A)}{sB + C}$$

Derivation of Full Wave Rectifier Transfer Function:



$e(t) = |\sin \omega t|$

Represented by the sum of the following emf's

1) $e_1(t) = \sin \omega t$; zero at t 0

2) $e_2(t) = \sin \omega t$; zero at t h to cancel remainder of $e_1(t)$

3) $e_3(t) = \sin \omega t$; zero at t h to provide the positive loop shown between h and 2 h

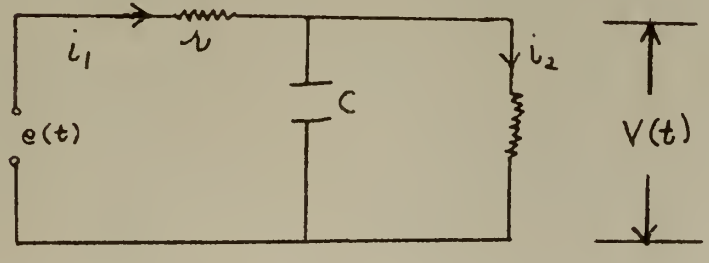
4) $e_4(t) = 2 \sin \omega t$; zero at t = 2 h to cancel the remainder of $e_3(t)$ and to supply the positive loop between 2 h and 3 h

$\therefore e(t) = \sin \omega t + 2 \sin \omega (t - h) + 2 \sin \omega (T - 2h) + 2 \sin \omega (t-3h)$

$+ 2 \sin \omega (t - nh)$

where $nh \leq t \leq (n+1)h$

$\bar{e}(s) = \frac{\omega}{s^2+\omega^2}(1 + 2e^{-hs} + 2e^{-hs} \ldots + 2e^{-nhs})$



Smoothing Circuit

$i_1 = \frac{dq}{dt} + i_2$ $\qquad q = C\,v(T)$

$$i_a = \frac{v(t)}{R} \qquad \frac{dq}{dt} = C \frac{dv(t)}{dt}$$

$$e(t) = r i_1 + v(t)$$

$$v(t) = e(t) - r\left[\frac{v(t)}{R} + C \frac{dv(t)}{dt}\right]$$

$$v(t) = e(t) - \frac{r}{R}\left[v(t)\right] - r C \frac{dv(t)}{dt}$$

$$\bar{v}(s) = \bar{e}(s) - \frac{r}{R}\bar{v}(s) - r C s \bar{v}(s) + r C v(0)$$

$$\bar{v}(s) + \frac{r}{R} v(s) + r C s \bar{v}(s) = \bar{e}(s) + r C v(0)$$

$$\bar{v}(s)\left\{1 + \frac{r}{R} \cdot r C s\right\} = \bar{e}(s) + r C v(0)$$

$$v(s)\left\{r C\left(\frac{1}{rC} + \frac{1}{RC} + S\right)\right\} = \bar{e}(s) + r C v(0)$$

$$r C \bar{v}(s)\left[\left\{\frac{R+r}{rCR}\right\} + s\right] = \bar{e}(s) + r C v(0)$$

$$r C \bar{v}(s)\left[\frac{R+r}{rRC} + s\right] = \bar{e}(s) + r C v(0)$$

$$\bar{v}(s) = \frac{\bar{e}(s)}{r C\left[\frac{R+r}{rRC} + s\right]} + \frac{C r v(0)}{C r\left[\frac{R+r}{rRC} + s\right]}$$

$$\bar{v}(s) = \frac{\bar{e}(s)}{r C\left[\frac{R+r}{rRC} + s\right]} + \frac{v(0)}{\left[\frac{R+r}{rRC} + s\right]}$$

Let $a = \dfrac{R + r}{r R C}$ $\qquad b = r C$

$$\boxed{\bar{v}(s) = \frac{\bar{e}(s)}{b\left[a + s\right]} + \frac{v(0)}{\left[a + s\right]}}$$

Now $\bar{e}(s) = \dfrac{\omega}{S^2 + \omega^2}\left[1 + 2 e^{-hs} + 2 e^{-2hs} \ldots + 2 e^{-nhs}\right.$

$$\therefore \quad v(s) = \frac{\omega}{s^2+w^2}\left[1 + 2e^{-hs} + 2e^{-2hs} + \ldots + 2e^{-nhs}\right] + \frac{v(0)}{[s+a]}$$

$$b(s+a)$$

Now there are 3 roots:

$s_1 = -a$

$s_2 = jw$

$s_3 = -jw$

For $s_1 = -a$

$$v_1(t) = \frac{w e^{-at}\ (1 + 2e^{-hs} + 2e^{-2hs} \ldots + 2e^{-nhs})}{(b)\left[a_1^2 + w^2\right]}$$

$$= \frac{w e^{-at}}{b\left[a_1^2+w^2\right]}\left[2\,\frac{e^{ah(n+1)}-1}{e^{ah}-1} - 1\right]$$

General expression:

$$v_1(t) = \frac{\left(w e^{-at}\right)}{b\,(a_1^2 + w^2)}\left[\frac{2e^{ah} - \{e^{-nah}\,(1 + e^{ah})\}}{e^{ah} - 1}\right] \qquad 0 \leq t \leq h$$

as $n \longrightarrow \infty$

$$v_{n\to\infty}(t) = \left[\frac{2w e^{-at}}{b\,(a_1^2 + w^2)}\right]\frac{1}{1 - e^{-ah}} \qquad 0 \leq t \leq h$$

The solution for

$s_2 = + jw$

$$v_2(t) = \frac{e^{jwt}}{b\,(a_1 + jw)\,2j}\,(1 + 2e^{-jwh} + 2e^{-j2wh} + \ldots + 2e^{-jnwh})$$

By definition

$$h = \pi/\omega = \frac{\pi}{2\pi f} = \frac{1}{2f}$$

$$\therefore \quad v_2(t) = \frac{e^{j\omega t}}{b\,(a_1 + j\,w)\,2\,j} \qquad (1 + 2\,e^{-j\pi} + 2\,e^{-j2\pi} + 2\,e^{-j3\pi} + 2\,e^{-jn\pi})$$

exponential series is equivalent to $(-1)^n$

$$v_2(t) = \frac{(-1)^n \quad e^{j\omega t}}{b\ 2\ j\ (a + j\,w)}$$

Now shift the origin to nh by the substitution of $t + n\,h$

or $t + \frac{n\pi}{\omega}$ for t

$$v_2(t) = \frac{(-1)^n\, e^{j\omega t}\, e^{jn\pi}}{b\ 2\ j\ (w_1 + j\,w)}$$

$$= \frac{e^{j\omega t}}{2\,b\,j\,(a + j\,w)} \qquad 0 \leq t \leq \pi/\omega$$

In a similar manner, the portion of the solution corresponding to

$s_3 = -j\,w$ will be

$$v(t_3) = \frac{e^{-j\omega t}}{r\,C\,2\quad (a - j\,w)} \qquad 0 \leq t \leq \pi/\omega$$

Now the complete solution is

$$v(t) = \left(\frac{1}{r\,C}\right)\frac{1}{(a^2 + w^2)}\left[a\,\mathrm{Sin}\,\omega t - w\,\mathrm{Cos}\,\omega t + w e^{-at}\,\frac{2\,e^{ah} - e^{-nah}(1 + e^{ah})}{e^{ah} - 1}\right]$$

When n is made very large, we have steady state action

$$v(t) = \frac{1}{r C (a^3 + w^2)} \left[a \operatorname{Sin} w t - w \operatorname{Cos} w t + \frac{2 w e^{at}}{1 - e^{ah}} \right] \quad 0 \leq t \leq h$$

$$\bar{i}_1(s) = \frac{1}{R} \left[\bar{v}(s) - C \bar{v}_1(s) \right]$$

$$\therefore \bar{i}_1(s) = \frac{1}{R} \left[\bar{v}(s) \right] \left[1 - K_o C \right] \quad \text{where } K = \text{Constant}$$

where $\bar{v}(s)$ = including initial conditions

$$v(t) = e(t) - r \left[\frac{v(t)}{R} + C \frac{dv(t)}{dt} \right]$$

$$v(t) = e(t) - \frac{r}{R} v(t) - r C \frac{d v(t)}{dt}$$

$$\bar{v}(s) = \bar{e}(s) - \frac{r}{R} \bar{v}(s) - r C [s] v(s) + r C v(0)$$

$$\bar{v}(s) = \bar{e}(s) - \frac{r}{R} \bar{v}(s) - r C s \bar{v}(s) + r C v(0)$$

$$\bar{v}(s) = \frac{\bar{e}(s)}{r C \left[\frac{R+r}{rRC} + S \right]} + \frac{C r v(0)}{C r \left[\frac{R+r}{rRC} + S \right]}$$

$$\bar{v}(s) = \frac{\bar{e}(s)}{r C \left[\frac{R+r}{rRC} + S \right]} + \frac{v(0)}{[A + S]}$$

Let $r c = B$ $\qquad \frac{R + r}{r R C} = A$

$$\bar{v}(s) = \frac{\bar{e}(s)}{B(A+S)} + \frac{v(0)}{(A+S)}$$

$$\bar{i}_1(s) = \frac{1}{R}\left[\frac{\bar{e}(s)}{B(A+S)} + \frac{v(0)}{(A+S)}\right]\left[1 - K_0 C\right]$$

$$\bar{i}_2 = \frac{v(t)}{R}$$

$$\bar{i}_2(s) = \frac{v(s)}{R}$$

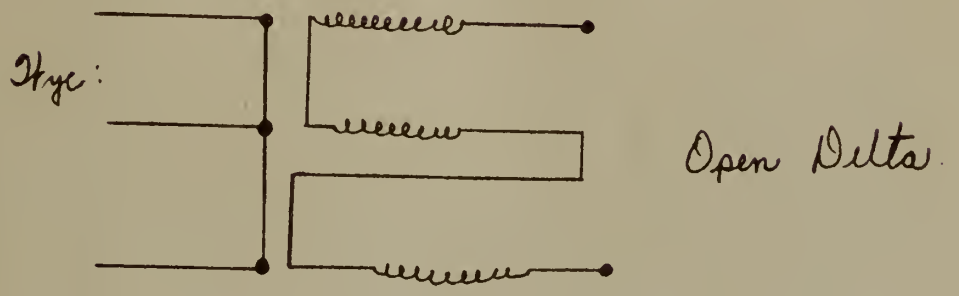
$$\therefore \bar{i}_2(s) = \frac{1}{R}\left[\frac{\bar{e}(s)}{B(A+S)} + \frac{v(0)}{[A+S]}\right]$$

$$\frac{\bar{i}_2(s)}{\bar{i}_1(s)} = \frac{\frac{1}{R}\left[\frac{e(s)}{B(A+S)} + \frac{v(0)}{(A+S)}\right]}{\frac{1}{R}\left[\frac{e(s)}{B(A+S)} + \frac{v(0)}{(A+S)}\right]\left[1 - K_0 C\right]}$$

$$\frac{\bar{i}_2(s)}{\bar{i}_1(s)} = \frac{1}{(1 - K_0 C)}$$

The Tripler Reactor:

In this unit the primary is connected wye while the secondary is connected open delta:



V A delivered:

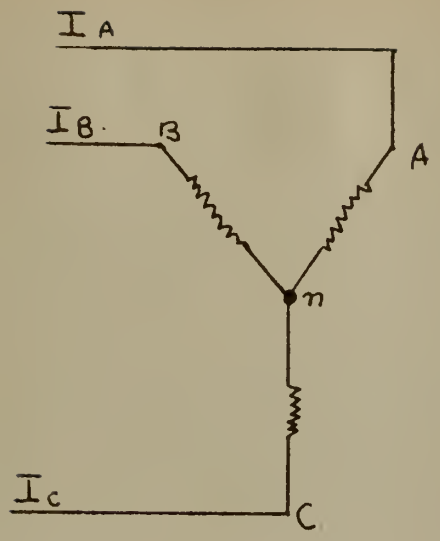
$3 V_p I_p = \sqrt{3}\ V_l\ I_l$

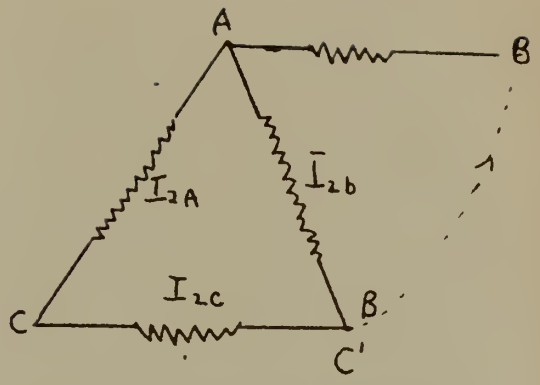
V A out of secondary - open delta

$\sqrt{3}\ V_2\ I_2$

Now the secondary - open delta means that ideally there is no fundamental but there will be a 3rd, 6th, 9th harmonic etc. because the core is well saturated. The predominant value of harmonic will be the 3rd.

The general type of expression for the Tripler Reactor for the Transfer function would be valid and is indicated below:





No fundamental on open Δ

Current

$I_{a1L} = I_{a1p}$

$I_{2ap} = I_{a1p} \frac{N_1}{N_2}$

Voltage

$V_{L1} = \sqrt{3}\, V_{p1}$

$\sqrt{3}\, V_{p1}\, N_2 = V_{p2}\, N_1$

$V_{p2} = \frac{V_p}{\sqrt{3}\ N_1/N_2}$

$V_{p_2} = \frac{V_p\ N_2}{\sqrt{3}\ N_1}$

Now the reduction of the V A rating for the normal delta when it is operated

open delta is 58%

Input V A = I_{a1} V_{L1} Wye connection

Output $= \left[\sqrt{3}\, a\, I\right] \left[V/\sqrt{3}\, a\right] = V A$ under normal conditions

Open Δ output : $\left[\frac{V}{\sqrt{3}\, a}\right] \left[a\, I\right] = \frac{V\, I}{\sqrt{3}}$

$$\frac{\text{Output}}{\text{Input}} = \frac{V\, I}{\sqrt{3}} \cdot \frac{1}{V\, I} = \frac{1}{\sqrt{3}} = 57.7\%$$

Now for an expression of the currents

The $I_1\ N_1$ must equal $I_2\ N_2$

Input I_L wye = I_p wye

$$I_p \text{ wye} = I_p \text{ delta} \left[\frac{N_\Delta}{N \text{ wye}}\right] \quad \text{Output}$$

$\therefore$ ratio of output to input is in the ratio of the turns N

Now the transfer function for the tripler reactor may be expressed as:

$$\frac{\mathcal{L}_o\ (s)}{\mathcal{L}_i\ (s)} = \left[\frac{N_\Delta}{N \text{ wye}}\right] \left[W\ (s)\right]$$ transformer as indicated in transformation for regular transformer.

APPENDIX III

Derivation of General Solution for Determining the Roots of a Cubic Equation

Fine's College Algebra:

General Solution of cubic equation:

(1) $x^3 - 3x^2 + 5x + 6 = 0$

Let $x = y + k$

$(y + k)^3 - 3(y + k)^2 + 5(y + k) + 6 \quad 0$

$y^3 + 3y^2k + 3yk^2 + k^3$

$- 3y^2 - 6yk - 3k^2$

$5y + 5k$

$+ 6$

$y^3 + y^2(3k - 3) + y(3k^2 - 6k + 5) + (k^3 - 3k^2 + 5k + 6)$

Now let $3k - 3 = 0$

$\therefore k = 1$

$y^3 + y^2(3 - 3) \quad y(3 - 6 + 5) + (1 - 3 + 5 + 6) = 0$

$y^3 + 2y + 9 = 0$

$\therefore$ the general cubic equation can be expressed as:

(a) $x^3 + px + q = 0$

with the x^2 term lacking.

Now let $x = y + z$

Substituting this expression in the above equation (a)

$y^3 + 3y^2z + 3yz^2 + z^3 + p(y + z) + q = 0$

(b) $y^3 + z^3 + (3yz + p)(y + z) + q = 0$

Now the variables y and z are subject to the single condition expressed in (b) one can impose the condition:

$$3yz + p = 0$$

(b) is reduced to $y^3 + z^3 + q = 0$

$$y^3 z^3 = \frac{-p}{27}$$

Now y^3 and z^3 are the roots of a quadratic equation of the form:

$$u^2 + qu - \frac{p^3}{27} = 0$$

$$y^3 = A = -\frac{q}{2} + \sqrt{\frac{q^2}{4} + \frac{p^3}{27}}$$

$$z^3 = B = -\frac{q}{2} - \sqrt{\frac{q^2}{4} + \frac{p^3}{27}}$$

This means that:

$$y = \sqrt[3]{A}, \quad W\sqrt[3]{A}, \quad W^2\sqrt[3]{A}$$

$$z = \sqrt[3]{B}, \quad W\sqrt[3]{B}, \quad W^2\sqrt[3]{B}$$

But from $3yz + p = 0$

the only pairs of the value of y, z which satisfy the desired conditions are:

	#1	#2	#3
$y =$	$\sqrt[3]{A}$	$w\sqrt[3]{A}$	$w^2\sqrt[3]{A}$
$z =$	$\sqrt[3]{B}$	$w^2\sqrt[3]{B}$	$w\sqrt[3]{B}$

Now if we apply these roots to

$$x + y = z$$

$$x_1 = \sqrt[3]{A} + \sqrt[3]{B}$$

$$x_2 = w\sqrt[3]{A} + w^2\sqrt[3]{B}$$

$$x_3 = w^2\sqrt[3]{A} + w\sqrt[3]{B}$$

where $A = \frac{-q}{2} + \sqrt{\frac{q^2}{4} + \frac{p^3}{27}}$

$$B = \frac{-q}{2} - \sqrt{\frac{q^2}{4} + \frac{p^3}{27}}$$

The general discussion of the solution:

If p and q are real, the character of the roots are dependent only on the value of

$$D \qquad \frac{q^2}{4} + \frac{p^3}{27}$$

(1) if $D > 0$, one root is real and two are imaginary

(2) If $D = 0$, all the roots are real and two are equal

(3) If $D < 0$, all the roots are real and unequal

Now if $D < 0$ this means that the discriminant is negative. Further A and B are conjugate imaginaries.

This means:

$$A = -\frac{q}{2} + i\sqrt{-\left[\frac{q^2}{4} + \frac{p^3}{27}\right]}$$

$$B = -\frac{q}{2} - i\sqrt{-\left[\frac{q^2}{4} + \frac{p^3}{27}\right]}$$

$$A = r(\cos\theta + i\sin\theta)$$

$$B = r(\cos\theta - i\sin\theta)$$

where

$$r = \left[\frac{q^2}{4} - \frac{q^2}{4} - \frac{p^3}{27}\right]^{1/2} = \left[-\frac{p^3}{27}\right]^{1/2}$$

$$\cos = \frac{-q/2}{r} = -\frac{q}{2}\left[-\frac{27}{p^3}\right]^{1/2}$$

$$w = \frac{(-1 \quad i\sqrt{3})}{2}$$

$$w = \frac{(-1 - i\sqrt{3})}{2}$$

$$x_1 = 2\sqrt[3]{r} \quad \cos \quad \theta/3$$

$$x_2 = 2\sqrt[3]{r} \quad \cos \quad \frac{\theta + 2\pi}{3}$$

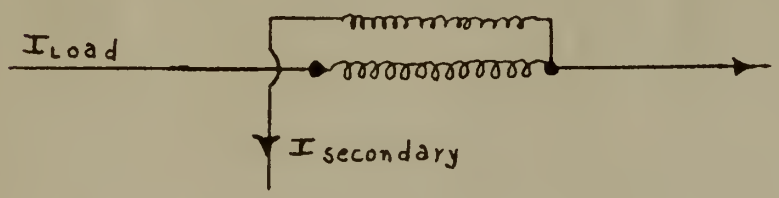
$$x_3 = 2\sqrt[3]{r} \quad \text{Cos} \quad \frac{\theta + 4\pi}{3}$$

APPENDIX IV

THE THEORY OF OPERATION OF THE VOLTAGE REGULATOR SYSTEM
AND THE
GENERAL CHARACTERISTICS OF THE MOTOR, CLUTCH, AND GENERATOR UNITS

To understand how the voltage regulator system functions effectively when operating properly, it is best to start with the building blocks which comprise the system. Consider the current loop first.

The current loop comprises the current transformer 27C68-2, the rectifier 44C20-2, and the final stage amplifier, 35D96-2. The current transformer is constructed such that the primary carries the output line current of the alternator while one leg of the secondary winding connects to the primary winding. This is shown in the following diagram:



This means that one part of the totally applied voltage to the regulator is the line to line voltage of the alternator. Now the physical construction of the transformer is such that the load current induces an emf in the secondary. This induced emf is the second component of the totally applied voltage to the regulator. The resultant voltage is the vector sum of these two voltages. Further, since the secondary winding can be considered as an inductor in series with the main power winding of the final stage amplifier at low loads, there will be a relatively large voltage drop across this inductor. However, as the load increases, there will be an induced emf in the secondary which will

counteract this drop. At no load then the applied voltage will be less than the line to line voltage of the alternator by the voltage drop in the secondary windings. The generator field current is a minimum, nonetheless the generator output tends to be greater than when load is applied. Thus there is some regulator action indicated exclusive of the voltage loop.

The purpose of the rectifier RECT 1 - 44C20-2 is to change the alternating current voltage to a direct current voltage which can be applied to the main power winding of the final stage amplifier.

Now the heart of the successful operation of the voltage regulator system is the magnetic amplifier. We must focus our attention on the three different windings which are embodied in the magnetic amplifier. These windings are the main power winding which is in series with the output circuit, the control winding, and the bias winding. These are shown schematically in figure 19 .

The purpose of the bias winding is to set the operation of magnetic amplifier to a predetermined condition such that with a given control current there will be the desired output current. The bias winding is wound such that it tends to saturate the core of the magnetic amplifier.

The control current for the final stage amplifier is the output current of the preamplifier. The control current winding is so wound that an increase of current will tend to desaturate the core. It is wound opposing the main power winding and the bias winding. Thus it can be seen that the output current will be a function of the main power current, the control current, and the bias current with due consideration of the respective polarities.

Now consider the voltage loop which consists of the Transformer T1-27C61-2, the Tripler Reactor L1-38B55-2, the Bridge Rectifier, Rect 1-44B30-2, and the Preamplifier 35C63-2.

The purpose of the transformer is to take the output voltage of the alternator which is the reference voltage and by using the wye delta combination obtain the desired input to the Tripler Reactor.

The Tripler Reactor is connected wye - open delta which means that the output voltage (secondary voltage) has a frequency of three times the fundamental of the input (primary) frequency. In addition the output voltage magnitude is three times the third harmonic output voltage of the delta. This increase in frequency is desirable from a rectification consideration because the ac ripple in the output of the rectifier will be much less than a 400 cycle ripple. This physically means that the output rectified voltage is closer to the ideal direct current voltage. Thus pulsation effects are diminished.

Now the control current for the Preamplifier, which is the output of Rectifier -144B30-2,will aid the main power winding in saturating the core. However, the bias winding opposes the main power winding, and will cause desaturation of the core. Thus the output current of the Preamplifier (Control Current Final Stage) is actually a function of the main power current, the control current, and the bias current, with due regard for the respective polarities.

Now that the respective building blocks are known, and we have specified the physical arrangement of the building blocks as indicated in figure 20-A, the following operations will result with an application of load.

The output voltage of the alternator instantaneously will fall. This means a reduced voltage out of the transformer and the Tripler Reactor, which means a lower value of control current for the Preamplifier. The main power current will likewise be reduced, due to decreased alternator voltage. The bias current will also be less.

Now consider the effect of saturating the Preamplifier core. The main power winding current and the control current winding are wound aiding, while the bias current winding is wound opposing. The control and main power current will cause desaturation, while the bias winding will cause saturation. The net effect will be desaturation relative to the cores magnetic state prior to the application of the load. Thus the output current (control current for the final stage) is reduced.

Now consider the current loop. With an increasing load current, there will be an increasing induced emf in the secondary of the current transformer. The vector sum of the induced emf and the line to line voltage of the alternator will cause an increased voltage across the Rectifier unit Rect 1-44C20-2.

Now the bias winding and the mainpower winding are wound aiding, while the control winding is wound opposing. There will be an increasing saturation of the core from the control current and the main power current,with desaturation from the bias current. The net effect will be saturation of the core, thus increasing the output current (generator field current) to compensate for the increase in load.

The various building blocks and general characteristics of the building blocks is indicated in the following list.

MOTOR-CLUTCH-GENERATOR SET

MOTOR

Manufacturer	Continental Elec. Co.
Type and Size	Induction - N324-X
Type of Rotor	Squirrel Cage
Horsepower Output	15
Speed (full load)	3530 rpm
Voltage	440 volts
Frequency	60 cycles
No poles	2
Connection	Wye
Stator Current	19 amperes
Phases	3
Torque Class	Normal
Current Class	Normal
Insulation Class	B
Ambient Temperature	50 deg. C
Duty	Continuous
Navy Service Classification	A
Mounting	Horizontal (Deck)
Degree of Enclosure	Drip - proof

MAGNETIC - PARTICLE CLUTCH

Model	32D67-2
Manufacturer	Vickers Electric Div.
Horsepower	10
Speed (normal)	3428

Maximum Slip	10%
Coil Voltage	2 volts
Coil Current	1.53 amperes
Degree of Enclosure	Drip - proof
Duty	Continuous
Ambient Temp. (max.)	50 deg. C
Navy Service Classification	A

GENERATOR

Manufacturer	Continental Elec. Co.
Type and Size	Synchronous - 324X
Rotor	Field
KVA	6.25
KW	5.00
Power Factor	0.80
Voltage	120 volts
Phases	3
Frequency	400 cycles
Speed (Synchronous)	3428
No. of poles	14
Stator Connection	2-wye
Stator Current	30 amperes
Field (Rotor) Voltage	125 volts, D-C
Field (Rotor) Current	1.5 amperes, D-C
Insulation Class	A
Ambient Temperature	50 deg. C
Duty	Continuous

Mounting	Horizontal (deck)
Degree of Enclosure	Drip - proof
Navy Service Classification	A

MOTOR CONTROLLER

Manufacturer	Ward Leonard Elec. Co.
Type	17039 - Across-The-Line
Size	2
Voltage	440 AC
Horsepower	15
Full Load Current	19 amperes
Phases	3
Frequency	60 cycles
Operation	Magnetic, Semi-Automatic
Duty	Continuous
Ambient Temperature	50 deg. C
Insulation Class	A
Degree of Enclosure	Drip - proof
Mounting	Bulkhead
Navy Service Classification	A

MASTER SWITCH

Manufacturer	Ward Leonard Elec. Co.
Type	MN 2322 - 1
Rating	440V, a-c, 5 amperes
Elements	1-two position rotary 1-momentary contact
Operation	Manual

Navy Service Classification	A
Insulation Class	A
Ambient Temperature	50 deg. C
Degree of Enclosure	Watertight
Mounting	Bulkhead

SPEED - REGULATOR

Manufacturer	Vickers Elec. Div.
Model	34E33-2
Input Voltage	120 volts a-c
Frequency	400 cycles
Input Current (max.)	4.5 amperes
Phases	1
Starting Circuit: Voltage	440 volts
frequency	60 cycles
current	0.1 ampere
phases	1
Parallel Operation	Yes
Control Type	Static Magnetic Amplifier
Duty	Continuous
Ambient Temperature	50 deg. C
Navy Service Classification	A
Degree of Enclosure	Drip - proof
Mounting	Bulkhead
Motor: horsepower	15
voltage	440 volts
phases	3
frequency	60 cycles

VOLTAGE REGULATOR

Manufacturer	Vickers Electric Div.

Model		34E25-2
Input Voltage		120 volts a-c
Frequency		400 cycles
Input Current (Max.)		4.5 amperes
Phases		3
Output Voltage (Max.)		125 volts d-c
Output Current (Max.)		1.75 amperes d-c
Starting Circuit:	voltage	440 volts
	frequency	60 cycles
	current	0.5 amperes
	phases	1
Parallel Operation		Yes
Control Type		Static Magnetic Amplifier
Duty		Continuous
Ambient Temperature		50 deg. C
Navy Service Classification		A
Degree of Enclosure		Drip - proof
Mounting		Bulkhead
Generator:	KW	5
	voltage	120 volts a-c
	phases	3
	frequency	400 cycles
	power factor	0.8

CURRENT TRANSFORMER

Manufacturer	Vickers Elec. Div.
Model	27C2-2
Primary Current	30 amperes
Secondary Current	1.25 amperes
Capacity	60 VA

Frequency	400 cycles
Phases	3
Ambient Temperature	50 deg. C
Navy Service Classification	A
Duty	Continuous
Degree of Enclosure	Open
Mounting	Switchboard

MANUAL AUTOMATIC TRANSFER SWITCH

Manufacturer	Electro Switch Corp.
Type	"P" Rotary navy packet
Voltage	125 volts a-c
Current (max.)	10 amperes a-c
Positions	4
No. of poles	10 - special throw
Ambient Temperature	50 deg. C
Navy Service Classification	A
Duty	Continuous
Degree of Enclosure	Open
Mounting	Switchboard

MANUAL CONTROL RHEOSTAT

Manufacturer	Vickers Elec. Div.
Type	45B5-2
Resistance	190 ohms
Current (max.)	0.35 ampere
Ambient Temperature	50 deg. C
Navy Service Classification	A

Duty	Continuous
Degree of Enclosure	Open
Mounting	Switchboard

APPENDIX V

COMPLETE DATA ON LOAD TEST FOR OVERALL SYSTEM

Date

Motor						Magnetic Clutch		Gen Fld		Speed	Generator										
V_{12}	I_1	V_{23}	I_2	V_{31}	I_3	V	I	V	I	RPM	V_{12}	I_1	V_{23}	I_2	V_{31}	I_3	W_1	W_3	ΣW	PF
																	122			

66

P&J 166-A

Motor						Magnetic Clutch		Gen Fld		Speed	Generator										
V_B	I_1	V_{23}	I_2	V_{31}	I_3	V	I	V	I	RPM	V_0	I_a	V_{23}	I_2	V_{31}	I_0	W_1	W_2	W	PF

Date

6

Date

Motor						Magnetic Clutch		Gen. Fld		Speed	Generator										
V_{12}	I_1	V_{23}	I_2	V_{31}	I_3	V	I	V	I	RPM	V_{12}	I_1	V_{23}	I_2	V_{31}	I_3	W_1	W_2	W	PF	

68 Feet 168

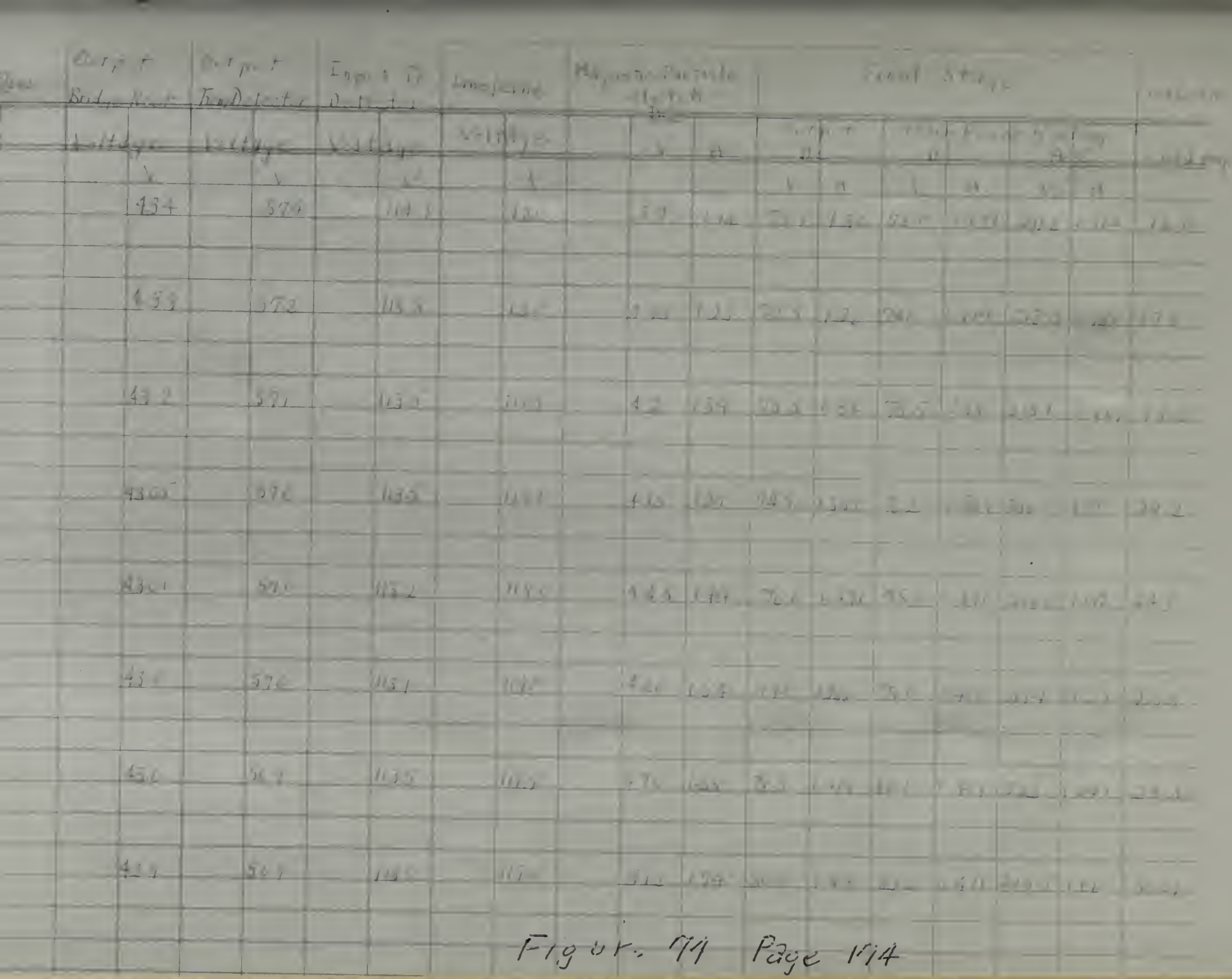
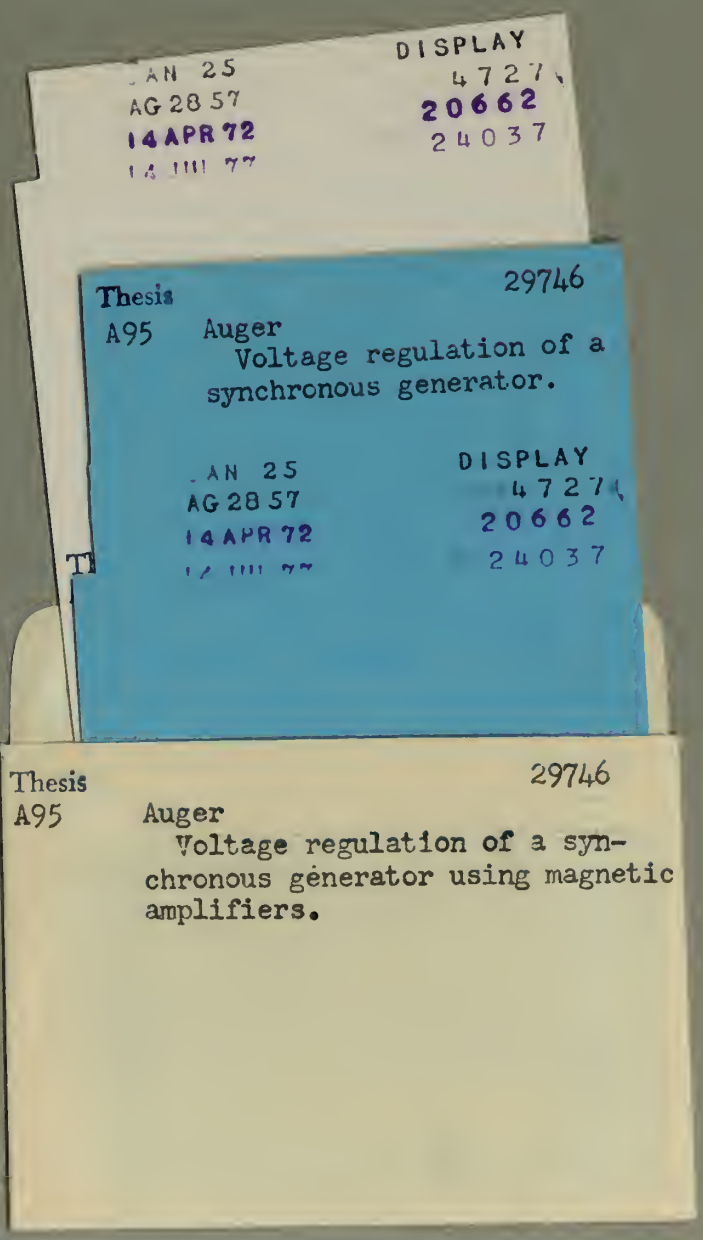


Figure 11 Page 114

7.5 Page 117.5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DISPLAY
4727
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24037
Thesis
A95 Auger
Voltage regulation of a synchronous generator.
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Voltage regulation of a synchronous generator using magnetic amplifiers.
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